

The Invisible Depletion: Compound Drought, Groundwater Collapse, and Maladaptation in the Middle East and Southwest Asia

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Key points

- A non-stationary "hot drought" regime has emerged, driven by asymmetric teleconnections and a severe thermodynamic tax on incoming moisture.
- A socio-economic maladaptation trap is driving emergency groundwater mining, pushing regional aquifers past irreversible physical tipping points.
- Droughts Early Warning Systems need to expand beyond traditional precipitation tracking to simultaneously monitor terrestrial water storage and evaporative stress.

Abstract

The Middle East and Southwest Asia (MESWA) region is experiencing severe hydro-climatic non-stationarity, transitioning from cyclical precipitation deficits and surpluses to a state of structural water bankruptcy. This review synthesizes the compounding atmospheric and anthropogenic drivers of this crisis, highlighting the region's shift towards a regime defined by frequent, concurrent extremes of drought and heat ("Hot Drought" regime). While fundamental ocean-basin teleconnections (e.g., El Niño Southern Oscillation) to MESWA remain intact, their hydrological impacts have become asymmetric, with the impact of drought-causing La Niña events remaining robust even while the wetter-than-normal conditions associated with El Niño have become less reliable. This asymmetry has emerged because (1) expected moisture delivery to MESWA has been frequently deflected by persistent atmospheric blocking and (2) escalating temperatures and extreme evaporative demand have reduced snow water storage and the ability of precipitation events to recharge surface moisture and water resources. To compensate for these losses in surface water availability, the region has increasingly relied on unregulated groundwater extraction. This dynamic has created a Water-Energy-Food-Ecosystems (WEFE) maladaptation trap where governments are forced to liquidate future aquifer reserves to prevent immediate food system collapse. This anthropogenic depletion, combined with the ongoing cryospheric buffer failure, has pushed regional basins past thresholds of historical elasticity—manifesting as irreversible physical degradation such as land subsidence, and coastal salinization—locking the corridor into a state where climatic variability alone is no longer sufficient to recharge water resources. We argue that operational Early Warning Systems (EWS) must expand beyond traditional, precipitation-centric meteorological forecasting by additionally tracking absolute systemic limits using Terrestrial Water Storage (TWS) and evaporative stress indices.

42 **Plain Language Summary**

43 The Middle East and Southwest Asia are moving from occasional dry spells to a state of
44 persistent water crisis, driven by severe "Hot Droughts." This shift is caused by a mix of
45 changing weather patterns and human actions. Persistent high-pressure weather systems are
46 blocking crucial winter storms from reaching the area that historically delivered rain to the
47 region. Meanwhile, extreme heat bakes moisture out of the soil and melts the mountain snow that
48 keeps rivers flowing during the summer. To survive this severe lack of water, farmers are
49 pumping water from deep underground. This traps the region in a vicious cycle where
50 governments must allow this unsustainable pumping to prevent immediate food shortages, even
51 as draining of these aquifers causes irreversible damage, including land-sinking and saltwater-
52 intrusion into fresh coastal groundwater. Because the resilience of the region's water system is
53 now compromised, predicting droughts solely by tracking rainfall is no longer sufficient for
54 water resource planning. To effectively prepare for future shortages, early warning systems must
55 look beyond just tracking rainfall and also measure the intense evaporation caused by the heat
56 and more actively track the rapid disappearance of the region's total underground water supplies.

1. Introduction

1.1. The Historical Context: Adaptation to Arid Variability

Drought is an enduring and recurring hazard across the arid and semi-arid mid-latitudes, particularly within the expansive hydro-climatic corridor extending from the Eastern Mediterranean, across the Iranian Plateau, and into the Hindu Kush of Afghanistan (hereafter referred to as the Middle East and Southwest Asia; MESWA). Historically, water supply and demand across this domain were maintained in a fragile but functional balance. Human water use patterns and agricultural systems were adapted to a high degree of natural climatic variability, enabling populations to cultivate and manage these arid environments for millennia (Kaniewski et al., 2012).

This historical stability was not underpinned by an absence of drought, but rather by the bounded, cyclical nature of the regional climate (Barlow et al., 2016; Cook et al., 2016). Traditional agricultural and pastoral systems relied on empirical predictability—specifically, the generational knowledge that the climate oscillated between distinct multi-year phases of surplus and deficit (Kaniewski et al., 2012). While these cycles are governed by large-scale ocean-atmosphere coupled modes—most notably the El Niño Southern Oscillation (ENSO), the Indian Ocean Dipole (IOD), and the North Atlantic Oscillation (NAO) (Barlow et al., 2016)—historical end-users adapted to their associated hydroclimatic variability as standard operational baselines. Multi-year precipitation deficits were a recognized, recurring feature of this regime, as cold-season rainfall anomalies across the MESWA corridor have a well-documented physical tendency to cluster in consecutive years (Hoell et al., 2023). Within this traditional paradigm, however, clustered dry years operated strictly as precipitation deficits; because they occurred prior to the onset of severe thermal forcing, ambient evaporative demand remained stable. Consequently, regional surface reservoirs and groundwater aquifers possessed the intrinsic buffering capacity to absorb multi-year dry sequences and recharge during subsequent wet phases (Voss et al., 2013; Sharifi et al., 2024).

1.2. The Emerging Crisis: Compounding Meteorological and Human Drivers

Over the past decade, this historical baseline in the region has been disrupted, characterized not merely by episodic precipitation deficits but by non-stationarity in both supply and demand. The most profound driver of this shift is background warming—averaging 0.45°C per decade across the MESWA region over the past four decades (1981–2019), reaching up to 0.6°C per decade in some territories (Zittis et al., 2022). This warming elevates evaporative demand to levels where even years with average precipitation fail to generate typical historical runoff volumes (Borhani Dariane & Ghasemi, 2026). For example, in Iran's Karkheh River Basin, average streamflow plummeted by more than 50% following a late-1990s climate shift, despite only an approximate 6% decline in precipitation, a discrepancy driven by a concurrent average 1.7°C temperature increase (Borhani Dariane & Ghasemi, 2026). Consequently, the historical precipitation-runoff relationship has weakened so substantially that increased precipitation no longer translates into proportional increases in runoff (Borhani Dariane & Ghasemi, 2026).

Furthermore, recent analyses of 45 years of global climate data demonstrate a widespread, significant increase in atmospheric evaporative demand driven by rising temperatures and vapor pressure deficits (Karimzadeh et al., 2025). Within the Middle East and North Africa (MENA) region specifically, potential evapotranspiration (PET) is projected to increase by up to 0.51 mm per year by the end of the century under intermediate emissions scenarios (SSP2-4.5), driving an alarming decrease in overall water availability (Ajjur & Al-Ghamdi, 2021). Consequently, the regional aridity index is projected to increase by up to 50% (Zittis et al., 2022). This transition toward hot drought degrades runoff efficiency; as evaporative losses outpace precipitation, annual water availability (defined as precipitation minus actual evapotranspiration) is projected to decline by up to 62 mm by 2100 under high-emission scenarios (Ajjur & Al-Ghamdi, 2021). Ultimately, this transition toward hot drought imposes a continuous thermodynamic tax (i.e., extreme heat and evaporation) on the entire hydro-climatic corridor.

Beyond local temperature and atmospheric demand, this regional baseline shift is driven by macro-scale atmospheric circulation adjustments across the Mediterranean and Middle East sectors (Francis & Fonseca, 2024; Kelley et al., 2015; Tuel et al., 2021; Ren et al., 2022) that disrupt moisture transport. For the focus region within the MESWA corridor, this macro-scale

shift manifests during winter as a persistent high-pressure barrier and an anomalous anticyclonic circulation anchored over the basin. Synoptically, this robust high-pressure system weakens and deflects the climatological, moisture-bearing westerly flow entering from the Mediterranean Sea, depriving the region of its primary source of winter precipitation (Kelley et al., 2015; Tuel et al., 2021). The resulting circulation anomaly forces an anomalous northerly-to-northeasterly wind regime that advects dry air over the Fertile Crescent, triggering severe regional moisture divergence and contributing to the instrumental drying trend (Kelley et al., 2015). Furthermore, these low-level surface impacts are coupled to upper-tropospheric jet dynamics (Tuel et al., 2021; Ren et al., 2022). Because the Mediterranean and Middle East sectors are situated along a zone of relatively weak vertical wind shear between the North Atlantic midlatitude jet, the North African subtropical jet, and the Middle East jet stream (MEJS), the regional external mode is highly barotropic (Tuel et al., 2021; Ren et al., 2022; Harnik et al., 2014). Consequently, near-surface circulation and regional winter hydroclimate exhibit an exceptional, mathematically demonstrable sensitivity to upper-level stationary wave disruptions (Tuel et al., 2021).

This meteorological shift is compounded by the fragility of the region's anthropogenic water systems. Twentieth-century infrastructure and agricultural policies were predicated on the assumption of climatic stationarity—the belief that wet years would return to refill surface reservoirs and recharge aquifers. As the frequency and efficacy of these atmospheric recovery events decline, a rigid reliance on supply-based management has accelerated resource depletion. Multi-decadal satellite monitoring, notably via the Gravity Recovery and Climate Experiment (GRACE), confirms this severe, multi-national decline in Terrestrial Water Storage (TWS), driven by the simultaneous desiccation of surface reservoirs and the rapid overdraft of underlying aquifers (Khaki & Hoteit, 2021). The resulting crisis is a manifestation of anthropogenic drought (AghaKouchak et al., 2021), where human demand and maladaptive land-use policies amplify natural scarcity, pushing the interconnected water, energy, and food systems toward systemic hydrological exhaustion where the region's water systems have been depleted beyond their natural capacity to recover.

However, it is critical to acknowledge that establishing definitive multi-decadal trends in MESWA's precipitation and runoff remains constrained by data uncertainty and product divergence (Hoell et al., 2024; El Kenawy et al., 2025; Zittis et al., 2018). Observed trends are

dependent on the selected period of record and the underlying configuration of individual datasets. For instance, while some studies or specific gauge-blended reanalyses might indicate monotonic precipitation declines in regions like Iran, satellite-derived products such as CHIRPS reveal a more stationary or volatile oscillatory baseline (Sun et al., 2018; Ghasemifar et al., 2023). Rather than weakening the argument for regional climate action, acknowledging this systemic divergence highlights a critical operational vulnerability: relying on single-variable precipitation datasets to define drought severity introduces profound epistemic risk. This analytical uncertainty highlights the urgent necessity for monitoring frameworks to pivot away from precipitation-only and toward multi-metrics that track thermal stress and total moisture deficits (Rezaei et al., 2023; FEWS NET. 2025).

1.3. Objective of the Review

To effectively manage water resources in this non-stationary future, it is imperative to move beyond traditional, precipitation-centric models of drought assessment. The objective of this review is to explore these physical and human drivers—both independently and in tandem—to provide an updated, comprehensive summary of water security issues across the Middle East and Southwest Asia (MESWA). By systematically examining how (1) changing atmospheric variability alters the regional response to established teleconnections, (2) the thermodynamic exacerbation of recent droughts, and (3) how these cascading hydrological impacts create a profound socio-economic maladaptation trap, this review paper aims to provide an updated understanding of the region's shifting hydroclimatic baseline. Ultimately, this synthesis is intended to guide the development of next-generation early warning systems: frameworks that explicitly account for increasing temperatures, rising atmospheric evaporative demand, and declines in terrestrial water storage to better support proactive adaptation in a rapidly changing environment.

2. Regional Climatology and Dominant Hydroclimate Teleconnections

2.1. The Historical Water Cycle and Topographic Buffering

Spanning from the Eastern Mediterranean coastline through the Iranian Plateau to the Hindu Kush, hydroclimate in the MESWA corridor is characterized by highly constrained seasonality

defined by a brief, concentrated winter wet season and a prolonged, hyper-arid summer. Historically, the region's hydrology has relied on the reliable arrival of winter precipitation (November to April). This moisture is predominantly delivered by mid-latitude westerlies, which carry synoptic-scale weather systems—most notably Cyprus Lows—from the Mediterranean Sea across the Fertile Crescent and into the interior highlands (Alpert et al., 1990). During the summer months (May to October), the northward migration of the subtropical high-pressure belt induces widespread atmospheric subsidence, effectively shutting off precipitation and driving extreme atmospheric evaporative demand.

Because the period of maximum precipitation is out-of-phase with the period of maximum agricultural water demand, the region's historical water security has been dependent on natural topographic buffering. High-altitude mountain ranges across the regional periphery function as critical "water towers" (Immerzeel et al., 2010). These elevations intercept winter cyclonic moisture, storing it as Snow Water Equivalent (SWE). The slow-release melting of this cryospheric reservoir acts as a temporal bridge; it buffers the subsequent summer dry season by sustaining the baseflow of the region's major transboundary river networks long after the winter storms have ceased (Darvishi Boloorani et al., 2024; Shokory et al., 2023; Vanham et al., 2008).

Understanding this historical stationarity—where reliable winter snowpack accumulation buffers the subsequent summer deficit—is essential for evaluating how macro-scale atmospheric teleconnections modulate interannual variability, and how anthropogenic thermodynamic forcing is now driving a severe, non-stationary departure from the historical norm.

2.2. The Atmospheric Baseline: The Westerlies and the Middle East Jet Stream (MEJS)

The stark seasonal contrast between summer aridity and winter precipitation in MESWA is governed by specific upper-level atmospheric features. During the summer months (JJA), the region is dominated by the descending branch of the Hadley cell and the expansive Asian monsoon anticyclone (ASMA). This broad-scale subsidence suppresses convection, resulting in near-total aridity and intense sensible heating across the Arabian Peninsula and the Iranian Plateau (Ziv et al., 2004).

Recent long-term analyses indicate that this summer anticyclone is not a stationary feature; its spatial extent, duration, and overall circulation strength have increased over the past four decades (El Kenawy et al., 2025; Hochman et al., 2022; Jaber et al., 2023; Lashkari & Mohammadi, 2019). Modern multi-reanalysis studies demonstrate a robust, accelerating expansion in the ASMA's physical area, alongside a pronounced lengthening of its seasonal duration—forming earlier in the spring and persisting later into the fall (Manney et al., 2021). Driven in part by intense mid-tropospheric warming over the Tibetan Plateau, the anticyclone has exhibited a pronounced decadal expansion along its western and northwestern edges, encroaching further over the Iranian Plateau (Basha et al., 2020). This spatio-temporal strengthening amplifies the broad-scale summer subsidence, lengthening the dry season and further entrenching the intense, sensible heating that drives the region's soaring evaporative demand. The transition seasons of fall (SON) and spring (MAM) are characterized by localized, highly variable convective precipitation, occasionally driven by the northward incursions of the Active Red Sea Trough, but these events rarely yield sufficient volume to sustain regional water resources (De Vries et al., 2013). Consequently, regional water supply relies almost entirely on the winter season (DJF) precipitation. During winter, the southward migration of the Intertropical Convergence Zone (ITCZ) and the expansion of the polar vortex allow the mid-latitude Westerlies to shift equatorward over the Mediterranean basin. This shift opens a critical atmospheric corridor, enabling the transport of marine moisture and the propagation of cyclonic disturbances into the continental interior, generating the precipitation and snowpack that sustain perennial river systems.

During this critical winter window, the propagation of cyclonic disturbances is guided by upper-level dynamics. Recent dynamical analyses have refined this understanding of the winter Westerlies, identifying the Middle East Jet Stream (MEJS)—a distinct, localized intensification of the broader Subtropical Jet—as the critical modulator of this moisture transport into the region (Schiemann et al., 2009). Operating in the upper troposphere (~200 hPa), the MEJS acts as an atmospheric waveguide, steering Mediterranean cyclones (e.g., Cyprus Lows) eastward across the Fertile Crescent and toward the Zagros and Hindu Kush mountain ranges (Enzel et al., 2015).

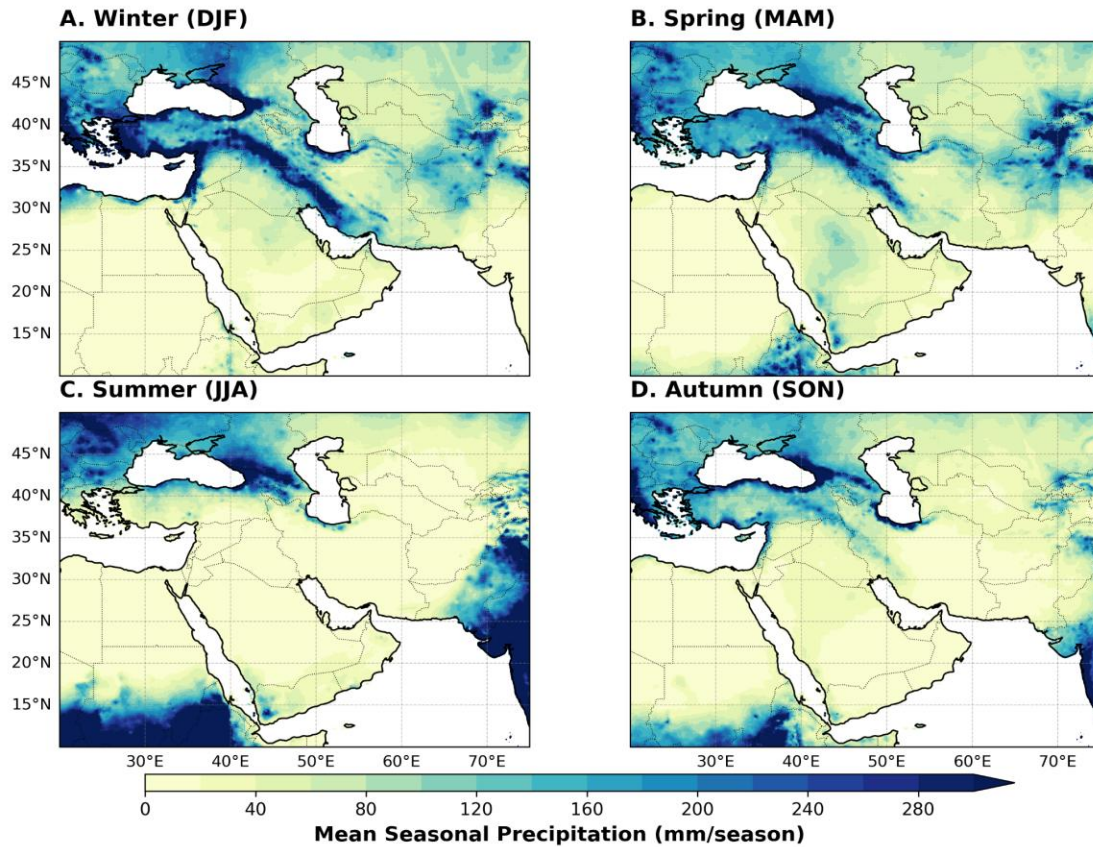


Figure 1: Baseline seasonal precipitation climatology across the MESWA corridor. Maps display mean seasonal precipitation accumulation (mm/season) derived from the CHIRPS v3.0 dataset (1981-2025). The region exhibits a skewed Mediterranean precipitation regime, with the vast majority of annual moisture delivered by cyclonic disturbances during the winter (A) and spring (B) seasons. In contrast, the summer months (C) are dominated by broad-scale atmospheric subsidence, resulting in near-total aridity across the region, while fall (D) serves as a localized, highly variable transition period.

Unlike the eddy-driven jets of North America, which are maintained primarily by high-frequency transient eddy vorticity forcing, the winter MEJS climatological core appears to be driven by temperature gradients. As demonstrated by Ren et al. (2022), the time-mean intensity and latitudinal position of the MEJS core (~200 hPa) are anchored by the thermal wind relation, governed by the strong broad-scale meridional temperature gradient between the cold Eurasian landmass to the north and the warm tropical Indian Ocean to the south.

At the synoptic-to-interannual scale, the dynamical response of this corridor to large-scale climate forcing is characterized by an equivalent barotropic structure (Hoell et al., 2013; Rezaei, 2023). Guided along the Middle East Jet Stream, low-frequency wave perturbations—including stationary planetary Rossby wave trains and persistent anticyclonic blocking features—anchor barotropic high-pressure anomalies over the region (Ren et al., 2022; Shaman and Tziperman, 2005, 2016; Wei et al., 2022). These anticyclonic structures suppress vertical moisture transport and deflect storm tracks away from agricultural heartlands (Hoell et al., 2024; Wei et al., 2022).

2.3. Historical Predictability: ENSO, NAO, and the Indian Ocean

For decades, seasonal forecasting and water resource planning across the MESWA corridor relied on historically stable, large-scale ocean-atmosphere teleconnections, primarily driven by the Pacific and Atlantic basins. The most dominant of these is the El Niño-Southern Oscillation (ENSO), which exerts its maximum influence over the region during the core winter (DJF) and early spring (MAM) wet seasons (Barlow et al., 2016; Hoell et al., 2024; Mariotti et al., 2002). Historically, positive ENSO phases (El Niño) generate anomalous cyclonic circulation over Southwest Asia, resulting in above-average winter precipitation (Hoell et al., 2024), a spatial pattern reflected in the positive anomalies across the northern and eastern sectors of the corridor (Figure 2a). The primary mechanism driving this connection is a Gill-Matsuno-type response, in which diabatic heating anomalies in the Indo-West Pacific force baroclinic and barotropic stationary Rossby waves poleward and westward of the heating (Hoell et al., 2013; Shaman and Tziperman, 2016). Furthermore, an eastward propagation serves as a secondary mechanism: eastward-traveling Rossby waves initiated in the equatorial Pacific reflect off the midlatitude jet and enter the North African-Asian jet to influence the Middle East (Barlow et al., 2002; Shaman and Tziperman, 2005). Conversely, La Niña phases are associated with increased convection in the west Pacific and a northward retreat of the jet stream, locking the region into persistent high-pressure subsidence and severe precipitation suppression (Barlow et al., 2016; Hoell et al., 2024), driving the widespread, severe moisture deficits across the entire central corridor observed in Figure 2b.

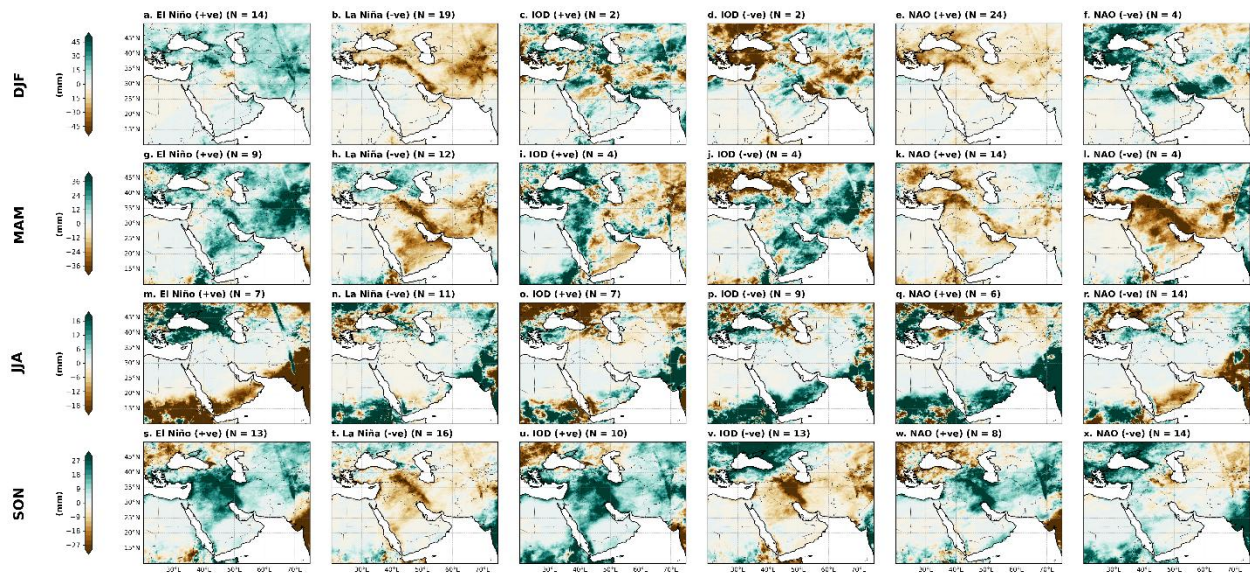


Figure 2: Seasonal precipitation anomalies associated with dominant large-scale ocean-atmosphere teleconnections across the Middle East and Southwest Asia (MESWA). Composite precipitation anomalies (mm/season) are shown for the positive (+ve) and negative (-ve) phases of the ENSO, IOD, and NAO. Rows correspond to the seasonal cycle: Winter (DJF; a–f), Spring (MAM; g–l), Summer (JJA; m–r), and Fall (SON; s–x). Precipitation data is derived from the CHIRPS v3.0 dataset relative to the 1981–2025 climatological mean. Teleconnection phases are classified using concurrent 3-month seasonal mean index values: El Niño and La Niña events are defined when seasonal mean Niño 3.4 SST anomalies exceed $\pm 0.5^{\circ}\text{C}$, respectively; $\pm$ ve IOD phases are defined when the Dipole Mode Index (DMI) exceeds $\pm 0.4^{\circ}\text{C}$; and $\pm$ ve NAO phases are defined when the seasonal NAO index exceeds $\pm 0.5\sigma$. Brown shading indicates regional moisture deficits (drying), while blue-green shading indicates moisture surpluses (wetting) relative to the seasonal climatology. Independent vertical colorbars (left) denote the anomaly magnitudes for each respective season, scaled to account for the region's highly variable seasonal precipitation baselines.

Simultaneously, precipitation variability in the western and northern fringes of the corridor has been modulated by the North Atlantic Oscillation (NAO), though it has generally been considered a secondary mechanism compared to the dominant Indo-Pacific drivers (Barlow et al., 2016; Rezaei, 2023). The mechanism here is driven by latitudinal shifts in the Atlantic storm track (Cullen and deMenocal, 2000; Cullen et al., 2002). During a positive NAO phase, the

Atlantic storm track travels further northward over western and northwestern Europe, leaving the Eastern Mediterranean, North Africa, and the Tigris-Euphrates headwaters anomalously dry, a spatial drying pattern as shown in Figure 2e (Cullen and deMenocal, 2000; Donat et al., 2014; Cook et al., 2016). During a negative NAO phase, this dynamic shifts, allowing Atlantic and Mediterranean cyclones to track further south on a more southerly storm track, delivering critical moisture to the Levant and northern Mesopotamia (Figure 2f) (Cullen et al., 2002; Donat et al., 2014).

Alongside the Pacific and Atlantic drivers, the Indian Ocean Dipole (IOD)—a coupled ocean-atmosphere phenomenon characterized by anomalous sea surface temperature gradients in the Indian Ocean—has long been recognized as a modulator of regional climate. The IOD acts as a critical secondary moisture source during the fall (SON) and early winter transition (Saji et al., 1999; Xu et al., 2021), with its most pronounced and consistent precipitation patterns occurring during the fall months (Figure 2u and 2v). A positive IOD, characterized by anomalously warm sea surface temperatures in the western Indian Ocean, enhances localized evaporation, strengthens lower-tropospheric southerly winds, and leads to anomalous moisture flux convergence (Chakraborty et al., 2006; Hoell et al., 2015). This dynamic pushes tropical moisture northward across the Arabian Sea, often acting synergistically with El Niño to prime the MESWA corridor's atmosphere for extreme precipitation events (Athar, 2015; Abid et al., 2020), reflected by the strong positive precipitation anomalies over the Arabian Peninsula and Iranian plateau (Figure 2u). On the other hand, negative IOD phases force severe fall season desiccation across these same southern territories (Figure 2v).

Recent statistical analyses suggest a necessary revision to the traditional hierarchy of these ocean-basin drivers. Using Independent Component Analysis (ICA) on drought indices, Rezaei (2023) found that Pacific drivers (PDO, ENSO) and the Atlantic Multidecadal Oscillation (AMO) explain a much larger proportion of variance in regional Middle East drought compared to the NAO. This statistical association supports the hypothesis that the region's hydro-climate is heavily oriented toward low-latitude, tropical, and multidecadal drivers (Rezaei, 2023). Consequently, the background state of the Indo-Pacific warm pool—and the capacity of the IOD to engage in constructive interference with Pacific signals—has emerged as a critical variable in assessing the region's overall predictability. This is evidenced by recent observations showing

that when ENSO and the IOD operate in tandem (in-phase), their coupled atmospheric circulation anomalies lead to stronger precipitation response over western Asia than when either operates alone; conversely, out-of-phase conditions destructively interfere to weaken the moisture delivery to the region (Abid et al., 2020; Hoell et al., 2024).

3. Atmospheric Interference and Non-Stationarity

3.1. The Indian Ocean Interference and Jet Stream Blocking

The spatial configuration of the Middle East Jet Stream (MEJS) serves as a primary element of hydrological outcomes across the corridor, dictating whether a season will be characterized by abundant moisture or severe deficit. Wei et al. (2022) identify the zonal extension of the jet as a critical mechanism governing this moisture delivery. Under historical baseline conditions, the core of the MEJS typically terminates over the Eastern Mediterranean. This specific alignment creates a favorable atmospheric environment, allowing moisture-bearing Mediterranean cyclones to penetrate inland, delivering essential winter precipitation to the Fertile Crescent, the Iranian Plateau, and the Hindu Kush (Hochman et al., 2022; Wei et al., 2022).

However, observational data from recent drought years indicates a deviation from this baseline: the jet extends further eastward, shifting its exit region toward the Hindu Kush (Wei et al., 2022). This eastward elongation is dynamically linked to the formation of a barotropic anticyclonic anomaly—a massive, persistent high-pressure system—anchored over the Arabian Sea and the Iranian Plateau (Wei et al., 2022). This atmospheric setup establishes a blocking pattern with profound consequences for regional moisture distribution.

During the critical winter wet season, the presence of this anticyclonic anomaly drives persistent subsidence, or sinking air motion, over critical agricultural and catchment zones, including the Levant and the Zagros Mountains (Wei et al., 2022). This subsidence effectively suppresses cloud formation and prevents precipitation, even when atmospheric moisture is present. Furthermore, this high-pressure dome acts as a physical barrier. These blocking patterns force the MEJS into a flattened, southward zonal flow, deflecting incoming Mediterranean cyclones away from the region's agricultural heartlands (Wei et al., 2022). Storm tracks are pushed either northward toward the Black Sea or southward into the Red Sea, effectively bypassing the areas

that rely on them most and exacerbating severe localized drought risks (Ghasemifar et al., 2023; Khosravi and Ouarda, 2025).

Recent spatial analyses by Khosravi & Ouarda (2025) support this mechanism, identifying localized drought hotspots that exhibit strong spatial correspondence with these anticyclonic anomalies. Their findings suggest that the severe and consistent drying observed in recent operational reports (e.g., FEWS NET) is a structural response to this jet elongation, which frequently locks the central corridor under a dome of subsidence and prevents moisture recharge (Khosravi and Ouarda, 2025). Furthermore, these atmospheric blockages increasingly occur in tandem with extreme temperature and atmospheric demand anomalies, transitioning the region into a regime of compound “Hot Droughts”. In this regime, enhanced background warming from greenhouse forcing heavily amplifies localized evaporative demand, severely reducing the hydrological efficacy of any incoming rainfall (Hoell et al., 2024).

Large-scale ocean-basin teleconnections, primarily the El Niño-Southern Oscillation (ENSO), remain the fundamental drivers of interannual precipitation variability across the MESWA corridor (Mariotti et al., 2002; Barlow et al., 2016). Both observational records and Earth System Models confirm that this underlying teleconnection is intact, indicating little difference in the baseline ENSO effect between past and recent climates (Hoell et al., 2024). For instance, the cold phase of ENSO (La Niña) continues to reliably force anomalous high pressure and severe precipitation deficits across the region (Barlow et al., 2002). However, utilizing these indices for operational forecasting is complicated by internal climate variability and competing regional drivers (Swenson et al., 2019; Rezaei, 2023). Further complicating this predictability, observational studies across the Arab region reveal that ENSO teleconnections exhibit strong spatial heterogeneity (Donat et al., 2014). Specifically, the NAO exerts stronger control over the extreme western fringes (such as the Mediterranean coastline and North Africa), whereas ENSO more strongly modulates the central and eastern portions of the corridor (Donat et al., 2014; Rezaei, 2023). Expected moisture delivery from an El Niño event can occasionally be masked by local land-atmospheric interaction interference or the expansion of persistent anticyclonic anomalies, which not only deflect incoming cyclones but also heavily amplify localized evaporative demand (Ju et al., 2024; Khosravi & Ouarda, 2025). The 2015–2016 El Niño serves as a critical case study of this dynamic; despite a historically strong equatorial Pacific signal,

expected moisture was blocked by persistent anticyclonic anomalies and thermodynamic forcing from the Indian Ocean (FEWS NET, 2015; Wei et al., 2022). Ultimately, these acute interference events highlight the necessity for Early Warning Systems to track compounding regional variables rather than relying solely on Pacific forcing (AghaKouchak et al., 2021).

This forecasting challenge was not isolated to the MESWA corridor. During the exact same 2015–2016 winter, analogous teleconnection failures were observed in other regions historically sensitive to El Niño, most notably Southern California. Climatological assessments of that season demonstrate that despite massive equatorial Pacific forcing, expected rainfall in California was largely suppressed by internal atmospheric variability, or “noise”, anomalous high-pressure ridging, and tropical heating interactions (e.g., Chen and Kumar, 2018; Singh et al., 2018; Jong et al., 2018; Swenson et al., 2019). The Middle East experienced a highly comparable disruption, indicating that the Pacific signal was affected by competing regional drivers and internal variability (Swenson et al., 2019).

In the case of the Middle East, the failure of the 2015 event to generate widespread regional recovery appears largely attributable to the Indian Ocean interference mechanism. The event coincided with substantial warming in the Western Indian Ocean, which generated a robust competing atmospheric response. As illustrated by the 500 hPa geopotential height anomalies in Figure 3, the atmospheric pattern over the corridor was fundamentally altered. Rather than forming a classic negative anomaly (trough) that invites Mediterranean cyclogenesis—as observed during the wet winter of 2018/2019—the winter of 2015/2016 was dominated by massive positive anomalies. These blocking highs, which are anchored to the north over Eastern Europe, the Black Sea, and Central Asia (Ghasemifar et al., 2023; Kelley et al., 2015), are dynamically linked to the eastward jet elongation discussed earlier.

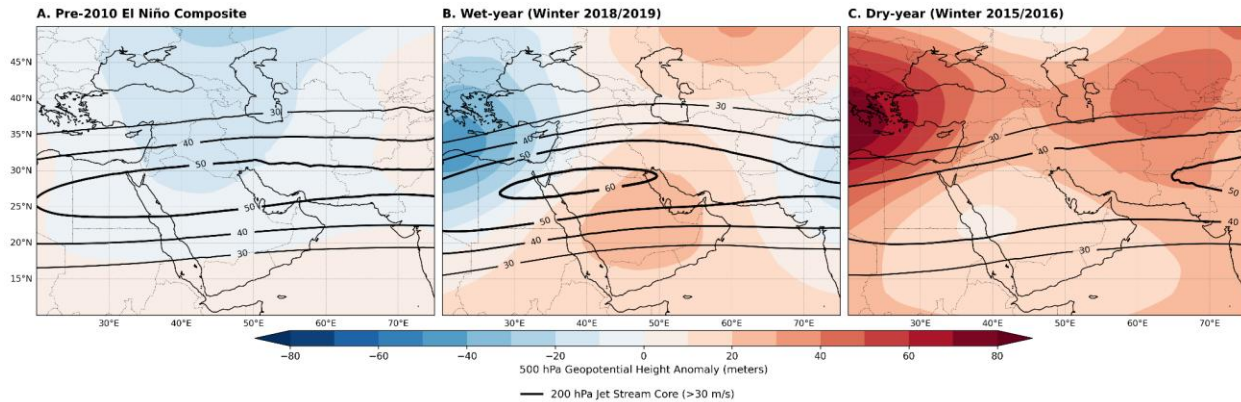


Figure 3: Maps of 500 hPa Geopotential Height Anomalies (shaded colors, in meters) overlaid with the 200 hPa MEJS core (black contours, winds > 30 m/s) for the winter season (Dec-Jan-Feb) relative to the 1981–2025 climatology, derived from ERA5 reanalysis. (A) A pre-2010 El Niño composite establishes the historical baseline, showing favorable troughing and a southward-dipping jet stream that reliably delivered winter storms to the region. (B) The 2018/2019 wet year demonstrates that when this historical troughing pattern occurs, it yields significant regional moisture. (C) The 2015/2016 hot drought year illustrates the modern blocking mechanism where a massive high-pressure ridge deflecting the jet stream, starving the corridor of incoming cyclonic storms.

These northern blocking features exerted immense pressure on the regional circulation (Wei et al., 2022), forcing the MEJS to flatten into a strictly zonal flow and squeezing its core southward. Consequently, the elongated jet stream bypasses the critical cyclogenesis zones of the Eastern Mediterranean (Ghasemifar et al., 2023; Wei et al., 2022), overriding the expected El Niño precipitation signal and effectively suppressing moisture delivery to the continental interior (Jong et al., 2018; Kelley et al., 2015).

The outcome on the ground was a deceptive green drought (FEWS NET, May 2016). While satellite vegetation indices (NDVI) in the spring of 2016 showed near-average greenness due to timely light rains, this superficial agricultural greening masked a critical hydrological failure. In the regional headwaters, specifically the Hindu Kush, the snow water equivalent (SWE) peaked prematurely and melted rapidly due to the unseasonal warmth associated with the anomalous atmospheric patterns. This case study underscores a critical vulnerability in modern forecasting: even when Pacific forcing is exceptionally strong, thermal interference from the Indian Ocean can physically alter the region's atmospheric patterns, rendering the precipitation ineffective for long-term hydrological storage.

While the atmospheric blocking observed during the 2015–2016 winter highlights a severe disruption to historical moisture delivery, attributing this solely to permanent structural non-stationarity requires accounting for internal climate variability. Recent syntheses confirm the Indian Ocean is undergoing a greenhouse-gas-driven shift toward a positive IOD-like mean state, pushing the frequency of positive IOD events beyond the envelope of natural variability observed over the past millennium (Wang et al., 2024). This structural alteration is further evidenced by the emergent dominance of early positive IOD events, which have increased substantially in recent decades due to greenhouse-forced early summer monsoon onsets and intensified Bjerknes feedbacks (Sun et al., 2022). However, this anthropogenic forcing remains heavily modulated by internal multidecadal noise. Time of Emergence analyses demonstrate that while mean sea surface temperature shifts have already emerged from background variability, changes in mean rainfall variability may not fully emerge across models until 2050 or later (Wang et al., 2024). Consequently, while the thermodynamic and dynamical baselines have fundamentally altered (Sun et al., 2022; Wang et al., 2024), natural decadal variability continues to significantly mask, intercept, or amplify these greenhouse-driven atmospheric interferences.

3.2. Asymmetric Predictability and the Persistence of La Niña

While the interference mechanisms described during the 2015–2016 event indicate that El Niño's historical capacity to deliver wet years may be weakened by competing teleconnections, it is critical to emphasize that the broader ENSO teleconnection has not entirely decoupled from the region. Rather, the predictability has become asymmetric. Observational records indicate that the drought-inducing signal associated with the cold phase of ENSO (La Niña) remains robust across the MESWA corridor. While the historically "wet" signal of El Niño has become less reliable, La Niña continues to deliver severe precipitation deficits regardless of the epoch (Hoell et al., 2024).

During La Niña phases, the typical atmospheric setup favors anomalous high pressure and subsidence over the Middle East, shifting storm tracks northward, suppressing Mediterranean cyclogenesis and reducing moisture transport into the continental interior (Hoell et al., 2024). Unlike the El Niño wet signal—which must actively overcome potential Indian Ocean blocking ridges to reach the corridor—La Niña's dry signal operates in tandem with the region's background temperature warming trend. This compounding effect was observed during the

prolonged “Triple-Dip” La Niña of 2020–2023, which entrenched a multi-year moisture deficit and severely depleted soil horizons across the region (FEWS NET, 2025).

This asymmetry introduces a profound non-stationarity for water resources management. The historical climatological baseline assumed a cyclical balance where multi-year La Niña deficits would eventually be offset by El Niño surpluses. However, the current atmospheric diagnostics suggest an emergent regime where the deficit phases (La Niña) consistently succeed in generating severe meteorological drought, while the expected recovery phases (El Niño) are frequently altered or displaced by internal atmospheric variability and tropical thermal interference. This observed asymmetry—where drought-inducing teleconnections exhibit stronger consistency across events than those driving wet phases—reflects a broader global phenomenon. For example, multi-decadal assessments over Eastern and Southern Africa demonstrate a similar asymmetry in ENSO teleconnections across the region, where anomaly sign consensus is more robust during drought phases than during recovery phases (Cook et al., 2024). Likewise, the vulnerability of expected El Niño recovery phases to disruption by internal atmospheric variability has been noted in other mid-latitude regions, such as the failure of the 2015–2016 El Niño to alleviate drought in California (Jong et al., 2018; Singh et al., 2018). Consequently, relying on these historically “wet” teleconnections for hydrological recovery is becoming precarious.

4. Compound Drought

4.1. The High Temperatures and Evaporative Demand

Contemporary drought across the MESWA corridor is no longer defined solely by precipitation deficits. The region is experiencing a shift toward “Hot Droughts” characterized by extreme temperatures that severely exacerbate evaporative demand. The threat of these thermal anomalies is further amplified by their expanding temporal footprint. Extreme dry heat events—which are detrimental to plant and ecosystem health—are expanding beyond historical meteorological summers (Ivanovich et al., 2026). This temporal expansion broadens the window during which the atmosphere extracts moisture from the soil column.

The frequency of these compound drought and heat extremes has dramatically increased across the region since 1999 (Hoell et al., 2023). By comparing the recent operational era (1999–2022) to the historical baseline (1951–1998) using transient climate model ensembles, analyses reveal a critical bifurcation in regional forcing: while ocean-basin teleconnections like ENSO continue to modulate precipitation variability, anthropogenic forcing from greenhouse gases is now the dominant driver of the concurrent temperature and atmospheric demand extremes (Hoell et al., 2023). This anthropogenic warming is uniquely pronounced during the dry summer season, driven by a combination of direct radiative forcing and regional thermodynamic feedbacks. Fundamentally, rising greenhouse gas concentrations drive a continuous background warming trend across all seasons by enhancing downward longwave radiation (Evan et al., 2015; Vizzy et al., 2013). In the arid MESWA environment—which lacks soil moisture for evaporative cooling and possesses a limited soil heat capacity—this trapped radiative energy is primarily converted into sensible heat (Zittis et al., 2014). This intense, localized surface heating subsequently drives the dynamic intensification and westward expansion of the Persian surface thermal trough across the Middle East and North Africa, creating a feedback loop that further locks in and compounds the extreme summer temperatures (Lelieveld et al., 2016; Vizzy et al., 2013).

The cumulative impact of hotter and drier conditions is vividly apparent across the Arabian Peninsula, where observational reanalyses document a robust warming signal exceeding 1°C per decade in northern territories; this shift has effectively elevated the regional baseline, pushing historical peak summer temperatures of roughly 43°C toward a critical physiological and habitability threshold approaching 50°C (Lelieveld et al., 2016). Recent risk-based attribution utilizing CMIP6 ensembles confirms that daily maximums exceeding 50°C—events that were effectively impossible in the pre-industrial climate—have seen their recurrence likelihood increase by a factor of 10 to 1,000 solely due to human influence (Christidis et al., 2023). Because the saturation vapor pressure of air scales exponentially with rising heat, crossing these extreme temperature thresholds converts the atmosphere into a voracious competitor for surface water, measurably reducing the hydrological efficacy of incoming rainfall (Al-Sakkaf et al., 2024).



Figure 4: Regional MESWA Hydro-Climatological Timelines (1981–2025). Annual anomalies are spatially averaged across the MESWA domain. The region is locked into persistent, severe compound droughts (a, SPEI-6) driven by a significantly non-stationary warming trend in 2m Temperature (b), which directly forces an increase in Vapor Pressure Deficit (c). This extreme atmospheric thirst overrides periods of average precipitation (d), triggering systemic, cascading declines in both Root Zone Soil Moisture (e) and Terrestrial Water Storage (f).

As shown by the SPEI-6 drought index (Figure 4a), the region has transitioned into a state of persistent, compounding temperature-amplified drought. In this new compound regime, as temperatures rise (Figure 4b), the Vapor Pressure Deficit (VPD) increases (Figure 4c), meaning the atmosphere's capacity to hold water increases. This high VPD extracts moisture from the soil column and vegetation canopy so rapidly that even years with near-average rainfall (Figure 4d) fail to generate historically expected surface runoff (Cook et al., 2020). This dynamic fundamentally degrades the regional runoff efficiency—defined as the fraction of precipitation that becomes runoff. Recent modeling and observational constraints confirm that warming temperatures and enhanced atmospheric evaporative demand systematically partition precipitation away from runoff and toward evapotranspiration, thereby increasing the severity of hydrological droughts even under stable precipitation regimes (Lehner et al., 2019; Vicente-Serrano et al., 2020).

This creates a self-reinforcing (positive) land-atmosphere feedback loop as the initial soil moisture deficits (Figure 4e) directly trigger cascading drought-heat dynamics. When the desiccated soil loses its evaporative cooling capacity, the energy balance shifts dramatically toward sensible heat flux, which subsequently amplifies the intensity and duration of regional heatwaves (Osman et al., 2022). Ali et al. (2024) identify a sharp sensitivity of regional drought phenomena to these rising temperatures, suggesting that increasing PET rates are effectively taxing the soil moisture budget. Consequently, a higher volume of rainfall is now required merely to maintain historical vegetation baselines.

This compounding effect indicates that temperature-driven PET is increasingly becoming a dominant driver of drought severity, potentially surpassing precipitation deficits in overall importance (El Kenawy et al., 2025). This dynamic imposes a very high evaporative stress on the region, negatively affecting surface water availability by returning moisture to the atmosphere

before it can effectively infiltrate aquifers or reach strategic surface reservoirs. The cumulative toll of this tax is visually stark in the profound depletion of Total Water Storage (Figure 4f), reflecting both climate-driven desiccation and the anthropogenic over-extraction required to meet escalating agricultural water demands. Ultimately, the threshold for what constitutes a hydrological recovery event is constantly being raised by the increasing atmospheric demand and reduced hydrological efficacy, which could be thought of as a “thermodynamic tax”.

This thermodynamic tax is further amplified in the region's mountainous headwaters where snowpack storage is important. As established by the Mountain Research Initiative EDW Working Group (2015), high-mountain environments are experiencing warming at significantly faster rates than lower elevations. This Elevation-Dependent Warming (EDW) is driven heavily by the loss of surface albedo; as snow cover retreats, the newly exposed, darker land surfaces absorb more solar radiation, creating a localized positive feedback loop that aggressively accelerates warming. However, while absolute warming rates are amplified at higher altitudes, the greatest loss of snow cover extent occurs in the mid-elevation transition zones (approximately 2,000 to 3,000 m). Historical winter temperatures in these bands hover just below the freezing threshold, meaning that even marginal warming can force a phase shift causing storms to deliver rain rather than snow or driving earlier snowmelt. Higher alpine zones (above 3,000 m) generally remain cold enough to receive precipitation as snow, but the amplified EDW accelerates early spring melt and progressively thins the overall snow depth (Sadeqi et al., 2024).

This upward migration of the snowline directly jeopardizes regional water security. Mountainous watersheds across the broader Asian continent function as critical "water towers", where high-altitude snow and ice dictate the hydrology of downstream basins (Immerzeel et al., 2010). In these semi-arid systems, streamflow dependency on snowmelt scales with altitude—often surging to account for the vast majority of the critical spring and summer baseflow required to sustain river networks during the dry season. The reduction of this high-elevation SWE effectively liquidates the slow-release natural reservoir that buffers the region against meteorological drought, leaving downstream agricultural allocations exposed to the intensified atmospheric demand (Immerzeel et al., 2010).

Beyond elevation dependent warming, recent mass-balance tracking reveals that the broader High Mountain Asia water tower system are being systematically depleted by remotely-forced climate anomalies. Zhang et al. (2023) demonstrated that the changing oceanic climates in the North Atlantic are generating reduced moisture transport from prevailing westerlies, driving TWS declines across the southern Tibetan Plateau. The loss of snowpack further degrades the localized cold, high-pressure anomalies that are naturally maintained by the cryosphere's albedo and evaporative cooling (Shaman and Tziperman, 2005). As this thermal shielding weakens, it alters regional atmospheric circulation and reduces moisture supply to the north. This feedback loop expands the area of TWS deficit into previously stable zones, accelerating a macro-scale depletion of the region's total water storage (Zhang et al., 2023). Consequently, the loss of these cryospheric buffers is not merely a localized shift in runoff timing, but a systemic, teleconnected failure of the entire regional water supply.

4.2. Shifting Baselines and the Transition to Hot Drought

This amplification of drought severity, from increasing temperature and atmospheric demand, has driven a statistically significant structural break in the region's hydroclimate. The Iranian Plateau provides a stark example. Utilizing CORDEX regional climate models and observational data, Fathian et al. (2022) confirms significant increasing trends in the frequency of warm days (TX90p, daily maximum temperature >90th percentile) and warm nights (TN90p, daily minimum temperature >90th percentile) across the plateau, alongside a projected increase in the Warm Spell Duration Index (WSDI) – defined as the annual count of days with at least six consecutive days where daily maximum temperatures exceed the 90th percentile. This background warming establishes a thirsty atmosphere capable of consuming potential runoff before it can be captured by surface infrastructure.

As illustrated in Figure 5, this extreme atmospheric demand has fundamentally shifted the region's climatic baseline. This shift is also noted by recent observational datasets documenting a multi-decadal, warming-driven increase in actual evapotranspiration across terrestrial ecosystems, including portions of the MESWA region over varying historical time intervals (Wang et al., 2022; Yang et al., 2023). Because this accelerated hydrological cycle results in a significantly greater loss of land surface water to the atmosphere (Wang et al., 2022), the

historical relationship between precipitation and effective water availability has been severely altered; modern years consistently require higher precipitation simply to offset the extreme evaporative demand, pushing the system into a persistent Hot Drought regime.

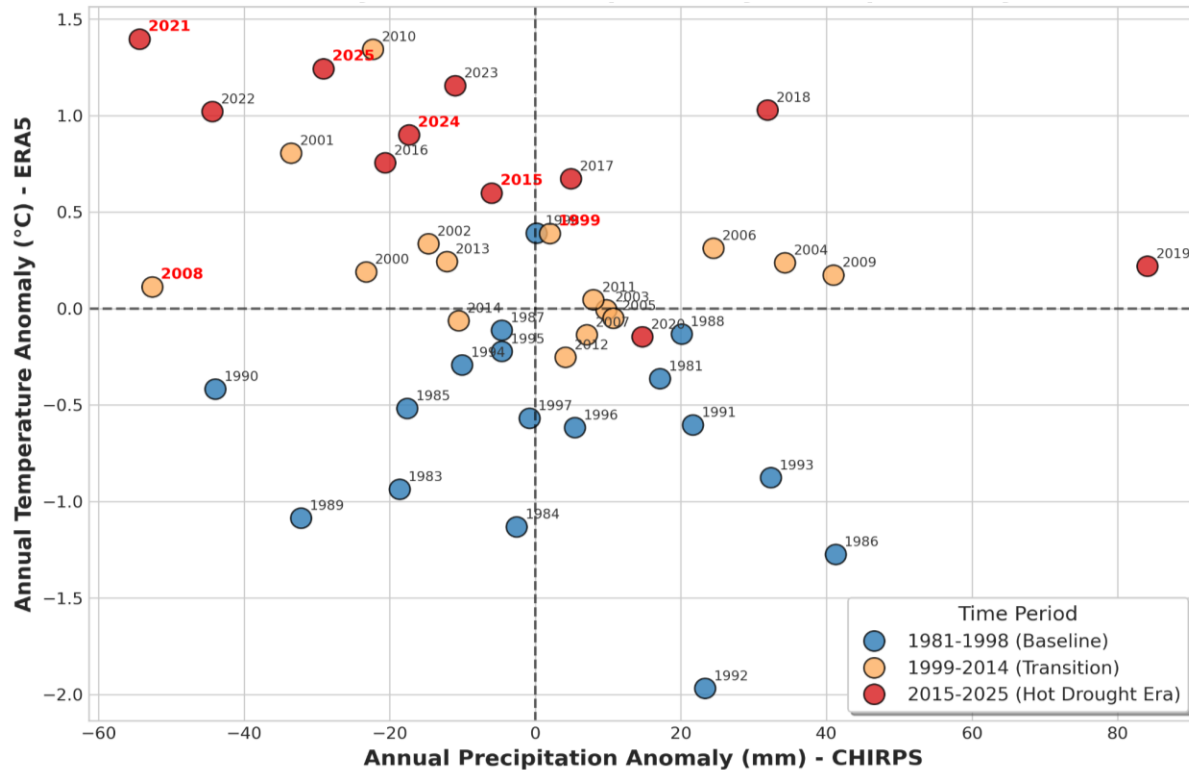


Figure 5: The transition to a Hot Drought regime in Iran (1981–2025). Annual precipitation anomalies (CHIRPS v3.0) are plotted against annual mean temperature anomalies (ERA5-Land). The temporal shift from the historical baseline (blue) to the current era (red) illustrates the Thermodynamic Tax. Recent years are overwhelmingly clustered in the high-temperature quadrants, demonstrating that even years with near-average precipitation (e.g., 2015) are now subjected to extreme evaporative demand. Red-labeled years indicate major regional hydro-climatic shock events.

The temporal shift depicted in Figure 5—from the historical baseline (1981–1998) to the current era (2015–2025)—demonstrates that modern water years are overwhelmingly clustered in high-temperature quadrants. This clustering confirms a critical operational reality that even when atmospheric teleconnections succeed in delivering near-average precipitation (such as during the 2015 season), the incoming moisture is subjected to extreme evaporative demand. Consequently, meteorological inputs (precipitation) are increasingly suppressed by thermodynamic outputs (evaporation), effectively breaking the historical drought-recovery cycle that water managers

previously relied upon. Therefore, the region's escalating water bankruptcy is not solely the result of non-stationarity in the teleconnection patterns affecting drought, but also the consequence of a thermodynamic tax that increasingly overrides the benefits of favorable synoptic conditions.

Long-term observational data from stations across the Arab region support this operational reality, revealing significant non-stationary warming trends since the mid-20th century that have notably accelerated after the early 1970s (Adamo et al., 2022; Donat et al., 2014). This background warming manifests as a systemic rise in the frequency of warm days and nights, fewer cold spells, and elevated absolute extreme temperatures (Al-Sakkaf et al., 2024; Donat et al., 2014; Lelieveld et al., 2016; Zhang et al., 2005). As atmospheric evaporative demand decouples from historical baselines, it translates into significantly higher ET rates (Wang et al., 2022; Yang et al., 2023). This heightened atmospheric thirst persistently extracts moisture from the root zone and accelerates soil drying, overriding the benefits of incoming precipitation (Ali et al., 2024; FEWS NET, 2025). The systemic consequences of this atmospheric thirst extend beyond the shallow subsurface and are increasingly evident in the rapid decline of total terrestrial water storage (Rodell et al., 2018). Rather than driving the direct physical evaporation of deep aquifers, the imposed atmospheric thermodynamic tax and rising PET drastically increases crop water requirements and net irrigation demands (Ali et al., 2024; Alotaibi et al., 2023). Consequently, the agricultural sector is forced to amplify groundwater extraction to offset the moisture deficit and maintain yields, accelerating regional aquifer depletion (Mirzaei et al., 2019; Ashraf et al., 2021).

However, the broad spatial averaging of TWS across the MESWA corridor can conflate distinct, highly localized drivers of mass loss. For example, severe TWS declines across the Arabian Peninsula are predominantly driven by decades of sustained fossil groundwater mining for agricultural irrigation, which has severely depleted transboundary systems like the Wasia and Umm Er Radhuma aquifers (Altayyar et al., 2024). In stark contrast, TWS loss across the Iranian mountain ranges is significantly influenced by climate-induced physical alterations, notably long-term declines in mountain Snow Water Equivalent (SWE) and shrinking snow cover duration (Sadeqi et al., 2024). Ultimately, whether driven by direct loss of cryospheric buffering or anthropogenically amplified aquifer extraction, this compounding thermal forcing

demonstrates that increased temperatures and extremely elevated VPD are systematically drying the soil column and severely reducing the available water for agriculture.

5. Case Studies of Recent Hydrological Extremes

5.1. Afghanistan: Elevation-Dependent Warming and Hydro-Climate Whiplash

The impacts of the thermodynamic tax described in Section 4 are most acutely observed in the regional headwaters. Afghanistan, historically functioning as the Water Tower for the surrounding basins, and relying on snow and glacier melt for approximately 80% of its water resources, is experiencing a fundamental destabilization of its natural storage mechanisms (Favre and Kamal, 2004; Shokory et al., 2023). Shokory et al. (2023), in a comprehensive review of the nation's water resources, identify the rapid warming of the Hindu Kush cryosphere as the primary driver of this instability. Historically, the country's hydrology functioned as a predictable conveyor where winter westerlies (originating as Mediterranean cyclonic systems) deposited snow at high altitudes, which then slowly melted to sustain strategic basins like the Amu Darya and Helmand through the dry summer months (Shokory et al., 2023).

Rather than a uniform decline in water availability, recent streamflow analyses reveal a complex, basin-specific degradation of the cryosphere. In non-glaciated, snow-fed catchments like the Dawlatyar, historical river gauge data demonstrate a severe temporal shift, where peak discharge now occurs prematurely in the spring due to winter precipitation increasingly falling as rain and running off immediately, leaving the basin starved of water during the peak summer growing season (Shokory et al., 2023). At the same time, heavily glaciated northern catchments, such as the Taloqan and Keshem, are experiencing a glacial subsidy. In these rivers, summer flows remain temporarily elevated solely because the upstream glaciers are actively liquidating their long-term mass (Shokory et al., 2023). This regional transition from a slow-melting snowpack to rapid winter runoff bypasses both modern surface reservoirs and natural infiltration processes. Because the accelerated runoff fails to deeply percolate and recharge the alluvial aquifers, consequently starving the gravity-fed underground karez (qanat) systems (networks of underground tunnels that use gravity to move groundwater from mountain aquifers down to agricultural areas), triggering a cascading collapse of rural agricultural infrastructure (Macpherson et al., 2017; Shokory et al., 2023).

This leads to a severe hydroclimatic "whiplash" (Chen et al., 2022; Tan et al., 2023; McDermott, 2026), where winter rain-on-bare-earth events trigger winter flash floods while simultaneously guaranteeing subsequent spring and summer water deficits due to the loss of the cryospheric buffer (FEWS NET, 2025; GEOGLAM, 2026). Operational validation of this phenomenon was observed during the 2025–2026 winter season, where heavy storm systems drove catastrophic flash floods in western provinces of Afghanistan (killing 17 people and damaging agricultural land and homes in Herat in December, followed by January storms that resulted in 61 fatalities, destroyed infrastructure, and wiped out hundreds of livestock) even as regional snow water equivalent (SWE) remained well below average (GEOGLAM, 2026).

This dynamic is captured in Figure 6, which illustrates the long-term hydro-climatic forcing and terrestrial response across a 26-year timeline, demonstrating a non-stationary regime shift rather than an isolated anomaly.

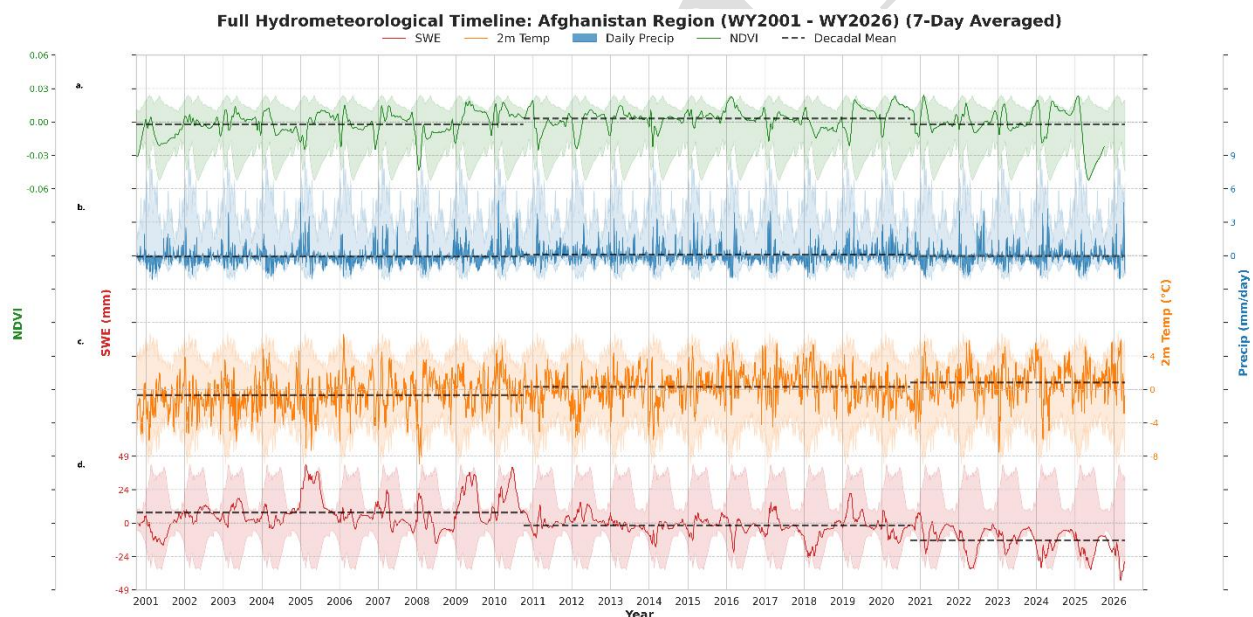


Figure 6: Multi-decadal hydro-climate whiplash and cryospheric collapse in Afghanistan (WY2001–WY2026). Data are derived from the Central Asia FLDAS dataset. The time series displays a 7-day running average of (a) MODIS derived NDVI (green line), (b) Daily Precipitation (blue line), (c) 2m Air Temperature (orange line), and (d) Snow Water Equivalent (SWE) (red line). Shaded envelopes represent the historical minimum and maximum bounds based on a WY2001–WY2025 climatological baseline. Dashed horizontal lines indicate decadal

step-changes (2001–2010, 2011–2020, 2021–2026), highlighting the progressive thermal forcing that culminates in the failure of the snowpack in recent years.

As the figure demonstrates, the severe deficit in SWE accumulation in the latter half of the record is not solely driven by a lack of incoming storms, but heavily by high temperatures and atmospheric demand forcing. The decadal means in panel (c) reveal a progressive, stepwise warming trend. During the most recent epoch (2021–2026), 2m air temperatures frequently breach the upper bounds of the historical envelope. Consequently, during critical winter storm events, mean air temperatures rarely reached the freezing point, significantly slowing down snow accumulation. High-intensity precipitation events that historically fell as snow arrived predominantly as liquid rain (Sadeqi et al., 2024).

This warming background acts as a catalyst for abrupt hydrological transitions, which are vividly illustrated by contrasting the precipitation and SWE panels (b) and (d) (blue and red lines, respectively, of Figure 6). While early-decade SWE routinely tracked within the historical envelope, the most recent years (2021–2026) exhibit signs of severe cryospheric collapse (UNESCO, 2026) with accumulation frequently tracking near or below historical minimums. This SWE deficit is not due to an absence of winter moisture; rather (as the red line demonstrates in Figure 6), these storms are now occurring because of warmer temperatures.

This phase shift highlights the physical mechanism behind the early-spring flash floods recently observed across Afghanistan, including the devastating April–May 2024 flood events. Driven by intense unseasonable rainfall interacting with severely degraded snowpacks and bare soil, these storms generated unprecedented instantaneous runoff that overwhelmed multiple river basins, resulting in hundreds of fatalities and widespread agricultural destruction (Zhang et al., 2025; World Weather Attribution, 2024).

The persistence of agricultural stress despite these high-intensity precipitation events is further explained by the thermodynamic tax of the warming atmosphere. Ali et al. (2024) identify a sharp sensitivity of regional drought phenomena to rising temperatures, noting that increasing PET rates continuously tax the soil moisture budget.

The physical degradation of this cryospheric buffer has directly triggered a rapid downstream reliance on groundwater reserves. As seasonal snowmelt volumes decline and arrive prematurely, surface irrigation networks fail to meet agricultural demand during the peak summer growing season (Shokory et al., 2023). To maintain crop productivity and avert immediate food insecurity, agricultural actors have increasingly turned to unmanaged, deep groundwater extraction across Afghanistan's alluvial basins (Kakar et al., 2025). This localized liquidation of subterranean reserves—largely unmonitored by traditional surface hydrometeorological networks—mirrors the broader regional transition from cyclical drought resilience to systemic water/groundwater bankruptcy (Madani et al., 2014; Madani et al., 2016).

As conceptualized by Madani (2014; 2016), water bankruptcy occurs when a nation's water consumption chronically exceeds its renewable supply, driven by an unsustainable, water-intensive development path and inefficient agricultural policies. Operating under a reactive "crisis management paradigm" characterized by severe "managerial myopia," regional actors continuously attempt to cure the immediate symptoms of drought (short-term crop failure) by engineering technical fixes like mining fossil aquifers, rather than addressing the root causes of over-allocation (Madani, 2014). This reflects a flawed thirst for "nature control" over sustainable "nature management," obscuring the reality that institutional and political mismanagement are far more influential drivers of the crisis than actual climatic or engineering limitations (Madani, 2014; Saatsaz, 2020). Consequently, this prioritization of immediate agricultural survival incentivizes independent actors to maximize their immediate gains at the cost of permanently degrading the aquifer infrastructure (FEWS NET, 2025; Madani, 2014), locking the basin into the WEFE maladaptation loop.

5.2. Iraq: Surface Water Bankruptcy and the Saline Wedge

While Afghanistan struggles with the degradation of its high altitude headwater systems, Iraq faces a horizontal and systemic crisis: the rapid depletion of surface water reserves and the subsequent intrusion of the sea and the desert. This horizontal vulnerability is fundamentally driven by Iraq's geographical position in the lower reaches of the transboundary Tigris-Euphrates River Basin. The vast majority of the annual discharge in the Tigris and Euphrates rivers originates not from local rainfall, but from the slow-release melting of winter snowpacks

in the Taurus Mountains of southeastern Turkey and the Zagros Mountains of Iran. However, this critical transboundary flow is collapsing, with warming winter temperatures reducing absolute snow accumulation and spring warming shifting the melt season approximately one month earlier, reducing critical river flow during the peak demand of the summer irrigation season (FEWS NET, 2025). This results in severe reductions in annual surface runoff—with models projecting mean annual discharge decreases ranging from 19% to 58% for the Euphrates and Tigris rivers by the end of the century—long before the rivers reach the Iraqi border (Bozkurt & Sen, 2013; Bozkurt et al., 2015; Adamo et al., 2022).

This crisis in the Mesopotamian basin is therefore a manifestation of compound stressors. Al-Maliki et al. (2022) describe this as a convergence of external and internal forcing; climate-driven flow reductions in the Tigris and Euphrates—amplified by the aggressive retention policies and extensive dam construction of upstream riparian states like Türkiye and Iran—collide with increased atmospheric demand (Adamo et al., 2022; Al-Maliki et al., 2022; Eltaif et al., 2024).

To fully grasp the severity of this thermodynamic tax, it is critical to recognize that even if upstream river flows were fully restored, Iraq's surface water remains subject to extreme evaporative demand (Al-Maliki et al., 2022). The independent, destructive power of this thermodynamic forcing is starkly illustrated by the recent desiccation of Sawa Lake in southern Iraq (Adamo et al., 2022). As a closed, groundwater-fed endorheic basin entirely disconnected from the Tigris and Euphrates river networks, its near-total volumetric collapse cannot be attributed to upstream dam construction or riparian flow disputes. Rather, the lake's desiccation is primarily driven by sharp increases in regional temperatures and the subsequent steep, non-linear rise in PET, compounded by the excessive withdrawal of water from surrounding wells (Adamo et al., 2022). Sawa Lake thus serves as an unambiguous, isolated proxy, providing empirical evidence that extreme thermal forcing and localized groundwater mining are actively depleting Iraq's water reserves independent of upstream anthropogenic flow modifications.

Crucially, the climatological baseline of Iraq itself is shifting. Even independent of upstream geopolitical tensions, the internal climatology of Northeast Iraq—the country's primary source region—is undergoing a statistically significant drying trend (Abbas et al., 2018). A recent

hydroclimatic assessment of the Kirkuk governorate—a key semi-arid agricultural zone in northern Iraq—validates this shift; predictive models project that historical mean annual runoff of 280 mm will plummet to just 110 mm by 2055 due to shifting precipitation regimes and climate-driven moisture deficits (Al-Hasani et al., 2024). This confirms that the domestic headwaters are rapidly drying out under the expanding influence of the Hot Drought regime.

The cumulative impact of these atmospheric and anthropogenic stressors has driven the basin into a state of structural water bankruptcy. Operational data from the 2025 FEWS NET Targeted Analysis shows that national water reserves plummeted from nearly 60 billion cubic meters in 2020 to 18 billion in 2024, and down to just 10 billion by late 2025 (FEWS NET, 2025). This systemic depletion is evident across all hydrological scales, from surface water to deep aquifers, as visualized in Figure 7.

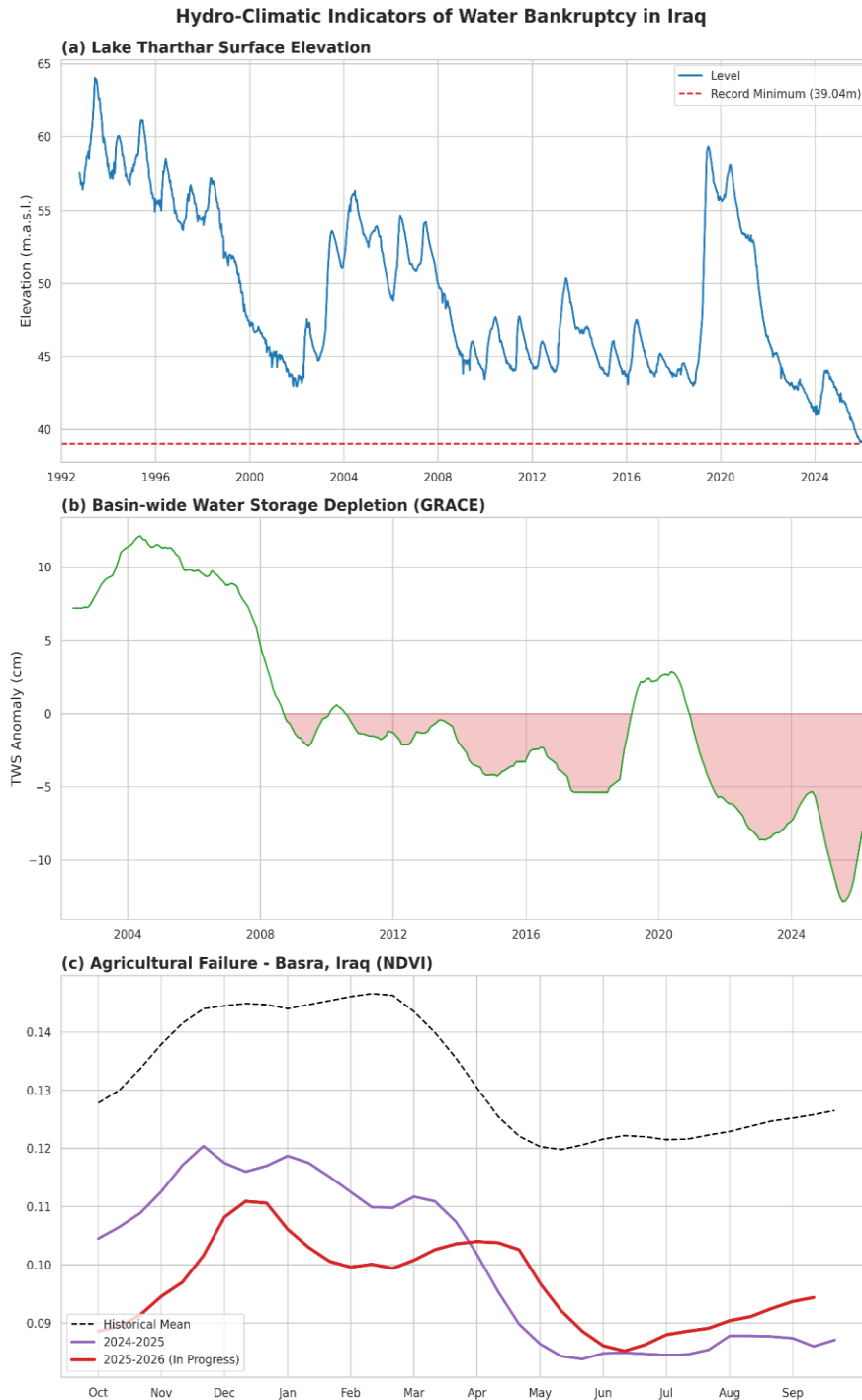


Figure 7: Systemic hydrological failure and water bankruptcy in Iraq. (a) Lake Tharthar surface elevation (meters above sea level) showing the collapse to a historical minimum by February 2026. (b) GRACE/GRACE-FO Terrestrial Water Storage (TWS) anomaly (6 Month SMA) for the Shatt al-Arab basin, illustrating the multi-year depletion of subsurface water. (c) Dekadal NDVI profiles for Basra, showing severe vegetation stress in the 2024–2026 seasons relative to the 2003–2022 mean, a proxy for saline-induced agricultural failure.

As shown in Figure 7, the sharp depletion of water levels within strategic surface infrastructure, such as Lake Tharthar (a), mirrors a multi-year depletion of total Terrestrial Water Storage (TWS) as captured by Gravity Recovery and Climate Experiment (GRACE) satellite data (b). Because of this massive reduction in the base flow of the Tigris and Euphrates, the outward hydraulic pressure necessary to resist saltwater intrusion from the Arab/Persian Gulf has been significantly disrupted.

Consequently, this hydraulic failure has allowed a saltwater wedge to penetrate over 100 km inland into the Shatt al-Arab basin (Al-Aesawi et al., 2021), resulting in severe vegetation stress, as reflected in persistent declines in normalized difference vegetation index (NDVI) at Basra (Figure 7c). As Al-Aesawi et al. (2021) note, plantations and wheat fields in this zone are dying not merely from an absolute lack of water, but because the available water has become too saline. The basin lacks the volume required to generate flushing flows, pushing the southern agricultural zones past an irreversible saline tipping point.

Simultaneously, the persistent soil moisture deficits have destabilized the northern landscape, inviting rapid desertification. Adamo et al. (2022) identify this as a dominant geomorphological shift; as the protective vegetation cover is lost to extreme evaporative demand, the erodible topsoil is mobilized. This dynamic has triggered a dramatic increase in the frequency and intensity of severe dust storms, signaling a physical phase transition in the landscape — a hallmark of expanding desertification and atmospheric instability across the MENA region (Boloorani et al., 2024). Ultimately, the combination of upstream flow reduction and downstream thermodynamic forcing has weakened the system's buffering capacity, rendering historical supply-based infrastructure nearly obsolete.

5.3. The Levant: Broken Seasonality and the Mediterranean Squeeze

The Levant presents a complex hydro-climatic signal where the general trend of aridification bifurcates into two distinct, yet interconnected, trajectories: the temporal contraction of the winter wet season and the spatial degradation of the arable coastal belt (the Mediterranean squeeze). To fully grasp the severity of these converging crises, it is necessary to contextualize the region's current hydrology against historical baselines. The recent multi-year drought events

in the Levant, specifically the 1998–2012 period, were likely the most severe in the last nine centuries (Cook et al., 2016). Indeed, high-resolution dendroclimatological analyses demonstrate an 89% likelihood that the 1998–2012 drought was the driest 15-year period in the last 900 years, and a 98% likelihood it was the driest since 1500 C.E. (Cook et al., 2016). Updated reconstructions confirm that these events likely remain the driest of the last 500 years, though uncertainties related to tree-ring proxy availability and selection remain (Anchukaitis et al., 2024). This paleoclimatic perspective confirms that the extreme aridity currently gripping the Eastern Mediterranean falls outside the bounds of natural multidecadal variability, suggesting a fundamental, anthropogenically driven shift in the regional baseline.

5.3.1. The Browning of the Fertile Crescent (East Levant)

In the agricultural lands of the East Levant—specifically Northeast Syria and inland Lebanon—this unprecedented drought severity has catalyzed a devastating compound stressor regime. That multi-year drought preceding the Syrian conflict was made two to three times more likely by anthropogenic climate change, which has driven a long-term trend of declining winter precipitation and increasing surface temperatures across the Fertile Crescent (Kelley et al., 2015).

This climate forcing intersected with decades of unsustainable land management. The pre-crisis agricultural policies heavily subsidized fuel for unregulated groundwater pumping, encouraging water-intensive crop cultivation in marginal zones (Aw-Hassan et al., 2014; Kelley et al., 2015). Specifically, the Syrian government subsidized diesel fuel at approximately 80% of its real cost, triggering an expansion of private artesian wells and severe, long-term aquifer drawdowns across the northern agricultural zones (Aw-Hassan et al., 2014).

Consequently, when the severe meteorological drought of 2007–2010 struck, the agricultural sector lacked its traditional fail-safe. Because the aquifers had already been systematically over-extracted during the preceding years to support cash crops, the water table had dropped below the reach of many wells. This meant the groundwater could no longer provide the necessary irrigation buffer to offset the lack of surface rainfall (Kelley et al., 2015). Satellite-derived vegetation health analyses (Sukkar et al., 2024) document a subsequent browning of the

landscape (Chen et al., 2022; Sukkar et al., 2024). Time-series analyses using Enhanced Vegetation Index (EVI) and NDVI data reveal that this severe degradation in northern Syria was driven not just by climate, but was fundamentally exacerbated by human activities—including conflict-induced land abandonment, irrigation failure, and a lack of seeds and fertilizers (Chen et al., 2022; Sukkar et al., 2024). The combination of intense thermodynamic tax, depleted groundwater, and conflict-driven infrastructure abandonment created a feedback loop of soil moisture loss and wind erosion. Notaro et al. (2015) demonstrated that this topsoil loss triggered a massive regime shift in regional aerosol loading; during the peak of the drought, the dying agricultural plains of the Fertile Crescent became a dominant dust source, generating dust storms that swept across the Arabian Peninsula. The region suffered a massive drop in harvested area—which plummeted by 40% in 2008 alone—and zero or near-zero production for small- and medium-scale farmers, causing the agricultural share of the national GDP to collapse from 25% to 17% (Kelley et al., 2015; Notaro et al., 2015). Consequently, this convergence of mass erosion and water bankruptcy stripped the Fertile Crescent of its agricultural resilience, forcing the mass displacement of up to 1.5 million rural farming and herding populations to the peripheries of Syrian urban centers just prior to the outbreak of civil unrest (Kelley et al., 2015).

5.3.2. Seasonal Compression and Coastal Salinization (West Levant)

Along the coastal corridor—encompassing Lebanon, the Palestinian coastal plain, and extending to the Jordan Rift Valley—the hydro-climatic crisis is characterized by a pronounced seasonal compression and redistribution of water delivery rather than a simple decline in annual precipitation totals (Hochman et al., 2022). Historically, this region relied on a stable winter wet season driven by Cyprus Lows. However, recent high-resolution reanalyses (e.g., Abu Arra & Şişman, 2025) indicate alteration in the timing and intensity of these deliveries. Recent precipitation patterns are shifting away from steady winter rainfall; instead, the region is experiencing a severe concentration of precipitation into fewer, more intense storm events. This manifests as a paradoxical increase in extreme daily rainfall intensity despite an overall decrease in total seasonal volumes (Alpert et al., 2002; Hochman et al., 2022). Moisture delivery is increasingly characterized by short, high-intensity storm events that deposit massive volumes of water at once, followed by extended, unseasonable dry spells. In Palestine, for example, the Short-term Standardized Precipitation Index (SPI-1 and SPI-6) reveals rapid, erratic oscillations

where wet periods are brief and unsustainable, rapidly giving way within weeks to severe agricultural droughts (Abu Arra & Şişman, 2025).

Recent climatological analyses demonstrate a severe calendar contraction of the historical Levantine wet season. Under future climate projections, the synoptic summer—defined by the hot, dry Persian Trough—is projected to expand by up to two months, extending the dry season to a six-month window (Hochman et al., 2018). In contrast, the synoptic winter, characterized by the occurrence of precipitation-bearing Cyprus Lows, is projected to contract by two months, compressing the active wet season into a narrow two-month window (Hochman et al., 2018). Because the regional water cycle is no longer characterized by a prolonged, steady winter recharge, the historical agricultural calendar has been compressed.

As illustrated by the decadal matrices in Figure 8, this temporal contraction is exacerbated by the thermal tax discussed in Section 4. While Figure 8 displays temperature anomalies, these drive severe climatic water deficits during the transition months. This temporal expansion is part of a broader non-stationarity, where extreme dry and humid heat seasons are expanding asymmetrically into these “shoulder seasons” (the months immediately preceding and following historical heat seasons) (Ivanovich et al., 2026).

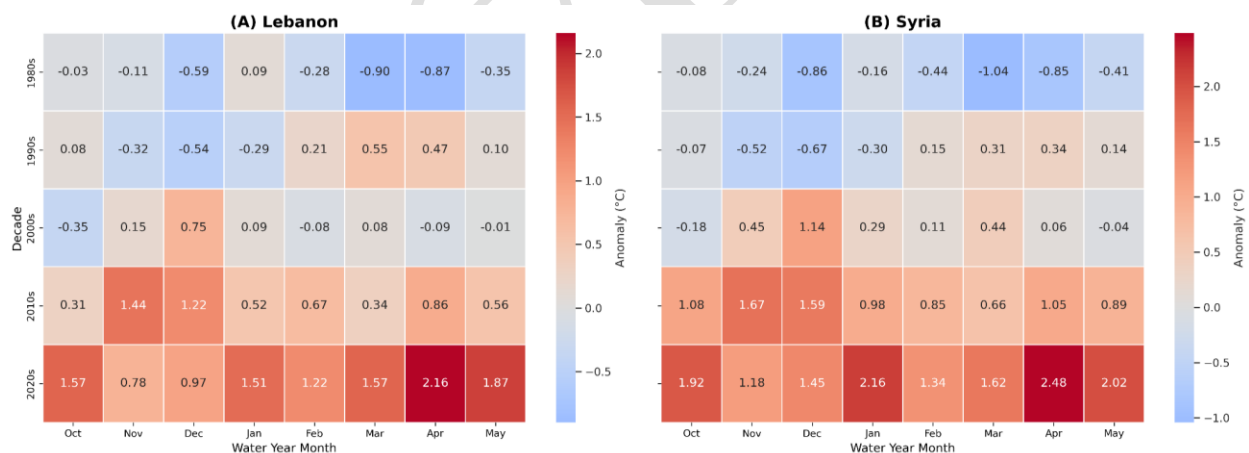


Figure 8: The expanding thermodynamic tax and temporal contraction of the Levant wet season (1981–2025). Decadal monthly temperature anomalies for the water year (Oct–May) relative to the 1981–2010 climatological baseline for (A) Lebanon and (B) Syria. Anomalies are calculated from spatially averaged ERA5-Land reanalysis data masked to national boundaries. The matrices demonstrate a shift from historically cooler baselines to a regime of severe thermal forcing in the 2020s.

The matrices in Figure 8 demonstrate a severe transition. The 2020s are characterized by extreme positive temperature anomalies (often exceeding $+1.5^{\circ}\text{C}$). When these thermal extremes occur during the shoulder months of the fall and spring, they exponentially increase PET. This increased thermal demand increases evapotranspiration of early and late-season rainfall before it can percolate, physically shrinking the essential window when water can successfully absorb into the soil to replenish groundwater, driving earlier and more severe agricultural drought (Elias et al., 2025).

On-the-ground observations confirm that this seasonal contraction is underway. In Lebanon, empirical drought feature assessments show that this temperature-driven moisture depletion has pushed the onset of the dry season 17 days earlier, delayed the fall season offset by 5 days, and extended the overall dry season duration by 15 days along the coast (Elias et al., 2025). This transition is further accelerated by approximately 0.1 mm/day increase in the rate of soil drying at the start of the dry season and a 10 mm reduction in the mean intensity of fall rainfall events, dismantling the transitional recharge period (Elias et al., 2025). In Palestine, this temporal compression concentrates over 60% of the total annual precipitation into a narrow window comprising December and January. While short-term agricultural droughts (SPI-1 and SPI-6) average 4 to 5 months, the accumulated water deficit extends hydrological droughts (SPI-12) to an average of 14 to 16 months, with extreme events lasting up to 46 months (Abu Arra and Şişman, 2025).

This seasonal contraction has severe consequences for coastal groundwater systems, where shortened recharge windows and high-intensity storms favor rapid surface runoff into the sea rather than deep soil percolation. In coastal zones under intense pressure, such as the Gaza Strip, this hydro-climatic deficit is compounded by ongoing geopolitical conflict and systemic blockade, creating a severe compound crisis (Al-Sibai, 2012; Eljamassi et al., 2023). While the physical recharge deficit accelerates seawater intrusion into the coastal aquifer (Eljamassi et al., 2023), border closures and lack of administrative sovereignty dismantle local adaptive capacity (Al-Sibai, 2012). Under these conditions, sewage and sanitation networks have suffered widespread failure, and critical water delivery and sewage pumps are often rendered inoperative due to severe electricity deficits and restricted fuel supplies for backup generators (Al-Sibai, 2012).

These compounding stressors—chronic groundwater degradation, increasing drought incidence, and destructive urban sediment hazards—stand as barriers to local adaptive capacity. As a result, a vulnerable population of more than 2 million people is continuously exposed to acute urban flooding events while simultaneously suffering from a collapsing freshwater security (Al-Sibai, 2012; Dawoud et al., 2023; Eljamassi et al., 2023).

6. Discussion: The WEF Nexus and the Maladaptation Trap

6.1. Anthropogenic Drought and the Invisible Depletion

The severe surface water deficits detailed in the previous case studies have triggered a profound shift in regional water management, forcing agricultural and municipal sectors to increasingly rely on groundwater reserves. This reliance has caused a parallel, and arguably more irreversible, crisis in subsurface storage. While meteorological drought initiates water scarcity, the current severity of the crisis is heavily driven by Anthropogenic Drought—a regime where human water demand and unsustainable land-use changes actively amplify natural scarcity, creating a cumulative moisture deficit that persists independently of climatic variability (AghaKouchak et al., 2021).

The scale of this invisible depletion is historically unprecedented. For example, national assessments reveal that Iran is currently among the top groundwater miners globally; its agricultural sector is responsible for more than 90% of groundwater consumption, resulting in 277 of its 609 plains — geographic water management units that do not strictly align with underground geological aquifers — falling into a critical condition of severe aquifer overdraft (Madani, 2014; Noori et al., 2023). Recent basin-scale assessments reveal that Iran's groundwater reserves suffered a staggering depletion of approximately 74 km³ between 2002 and 2015 alone, leaving nearly 77% of the country's land area under extreme aquifer overdraft (Ashraf et al., 2021). Rodell et al. (2018), using global GRACE satellite data, identified the Middle East as suffering the world's most severe rate of freshwater storage loss, attributing the majority of this deficit directly to anthropogenic groundwater pumping rather than meteorological drought alone. Recent applications of spatially refined Level-1B stacked regression to GRACE and GRACE-FO data demonstrate that this depletion is considerably more acute than historical estimates suggested. Traditional monthly mass concentration processing

techniques underestimated regional TWS trend magnitudes by an average of 33%, obscuring the true severity of agricultural groundwater mining in hotspots across the Fertile Crescent, the Arabian Peninsula, and Iran (O'Neill et al., 2026). While the severe negative correlation between rising temperatures and Terrestrial Water Storage (TWS) highlights a systemic collapse, it is crucial to analytically disentangle purely climate-driven surface desiccation from anthropogenic groundwater extraction. Satellite gravimetry, such as GRACE, captures absolute mass change but cannot distinguish between the evaporative loss of surface reservoirs and the volumetric removal of deep aquifers, as the satellites measure the total vertically integrated effect of mass changes (Tapley et al., 2004; Abou Zaki et al., 2019; Long et al., 2016). However, data assimilation frameworks and advanced hydrological modeling might resolve this attribution gap. Studies isolating these variables demonstrate that while extreme thermal forcing initiates surface water deficits and exponentially increases agricultural water demand, the vast majority of the absolute TWS mass loss across the MESWA corridor is attributable to the subsequent anthropogenic over-pumping of groundwater, rather than meteorological drought alone (Rodell et al., 2018; Joodaki et al., 2020).

Therefore, the strong correlation between temperature anomalies and TWS depletion represents a compound anthropogenic feedback loop where climate-driven shifts in both supply and demand converge to accelerate groundwater extraction (Joodaki et al., 2014; Voss et al., 2013). On the supply side, “Hot Droughts” reduce available surface water, soil moisture, and reservoir storage, forcing agricultural sectors to substitute surface allocations with groundwater extraction (Voss et al., 2013). For example, during the 2007–2009 drought in Iraq, the decline of the Qadisiyah Reservoir and transboundary streamflows prompted the rapid drilling of thousands of government and private wells as a supply-side compensation mechanism (Voss et al., 2013). On the demand side, rising atmospheric temperatures and vapor pressure deficits increase PET, which increases crop water requirements (Alotaibi et al., 2023; Elias et al., 2025). This thermal demand forces agricultural actors to increase pumping volumes of water to maintain vegetation health and offset rapid soil moisture depletion (Ali et al., 2024; Elias et al., 2025). Rather than a single pathway, the depletion of subsurface storage represents a dual forcing where a thirsty atmosphere increases irrigation demand as well as a drier landscape forces a reduction in water resources. This aggressive extraction pushes the region's aquifers toward a physical tipping

point: as water is rapidly drained from clay-rich aquifer systems, the underlying soil structure physically collapses. This manifests as severe, widespread land subsidence that permanently destroys the physical pore space required to store groundwater, structurally erasing the region's hydrological resilience (Sharifi et al., 2024).

As surface water allocations are routinely suspended due to the Hot Drought conditions, farmers have increasingly turned to unregulated, often subsidized, deep-well pumping to maintain production (Madani et al., 2016). For instance, in Syria, historical government policies heavily subsidized diesel fuel at approximately 80% of its real cost, triggering a massive expansion of private artesian wells and severe, long-term aquifer drawdowns across northern agricultural zones (Aw-Hassan et al., 2014). This shift is actively accelerated by domestic policy frameworks that prioritize crop production over sustainable water resources through subsidized energy. The availability of highly subsidized energy acts as a perverse economic incentive, allowing farmers to continuously deepen wells and effectively decouple the cost of water extraction from its physical scarcity (Mirzaei et al., 2019). This effectively mines fossil water to bridge a widening resource gap. Crucially, this gap is not solely the result of the meteorological teleconnection disruptions described in Section 3. Rather, it is driven by a convergence of compounding factors: severe precipitation deficits, the exponential increase in atmospheric evaporative demand (the thermodynamic tax), and the rapid intensification and expansion of water-intensive agriculture across marginal zones.

This aggressive extraction is pushing the region's aquifers toward a physical tipping point (Joodaki et al., 2020). As water is rapidly drained from clay-rich aquifer systems across the Iranian Plateau and the Afghan plains, the underlying soil structure physically collapses—a process manifesting as irreversible, widespread land subsidence (Kakar et al., 2025; Sharifi et al., 2024). For example, multi-sensor InSAR monitoring of the Tehran Plain—located within the heavily depleted Salt Lake basin, which alone lost 20 km³ of groundwater from 2002 to 2015 (Ashraf et al., 2021)—reveals subsidence rates exceeding 25 cm per year in western Tehran and 22 cm per year in the Varamin Plain (Haghshenas Haghighi & Motagh, 2019). Crucially, hydro-geodetic analyses confirm that this compaction is predominantly inelastic—a permanent deformation and breakdown of the soil matrix that irreversibly destroys the aquifer's historical storage capacity. With an estimated elastic-to-inelastic deformation ratio of approximately 0.4,

the majority of this subsidence represents a permanent structural failure of the aquitards (Haghshenas Haghighi & Motagh, 2019). Consequently, the region's hydrological resilience is being structurally erased. Even if favorable teleconnections were to return and generate above-average rainfall, the physical capacity of the ground to capture and store that moisture would have been destroyed, locking these basins into a state of water bankruptcy.

6.2. The WEF Nexus and the Socio-Economic Maladaptation Trap

The physical destruction of the region's aquifers is ultimately driven by a profound socio-economic lock-in. From a purely hydrological standpoint, the region must immediately stop over-pumping its groundwater in order to stabilize its rapidly collapsing water systems. However, halting this extraction presents an impossible, life-threatening dilemma. In heavily water-scarce environments, fluctuations in the supply or demand of a single subsystem destabilize other subsystems. In MESWA, pursuing rigid food security and regional self-sufficiency goals inherently exacerbates groundwater overexploitation and ecological degradation (Chang et al., 2025). Using global climate-water-food systems models, Perez et al. (2024) demonstrate the brutal trade-offs involved in trying to save the aquifers. Simulations that strictly enforcing sustainable pumping limits—without massive, unprecedented complementary investments in high-efficiency irrigation infrastructure, drought-resistant crop varieties, alternative livelihood programs, and substantial food import subsidies—would trigger an immediate, sharp decline in regional food production and a corresponding spike in food prices, growing the number of people at risk of acute hunger by 26 million by 2050 (Perez et al., 2024).

This trade-off creates what Drobinski et al. (2025) characterize as a “maladaptation trap”. When adaptation strategies focus narrowly on singular short-term goals—such as maximizing food production through intensive agriculture or deploying solar-powered groundwater pumps without regulatory safeguards—they often deepen interlinked vulnerabilities and cause unintended rebound effects that paradoxically encourage greater water use (Drobinski et al., 2025). For example, the deployment of heavily subsidized fuel and modern, high-efficiency drip irrigation technologies across the MENA region, initially intended to save water, has frequently triggered a rebound effect, further accelerating aquifer exhaustion by enabling the rapid expansion of water-intensive cash crops into previously marginal zones (Aw-Hassan et al., 2014; Bouhioui and

Loudyi, 2025). Consequently, there is a significant, unavoidable trade-off between intensive food production and other components of the Water-Energy-Food-Ecosystems (WEFE) nexus that must be explicitly acknowledged and managed within cross-sectoral adaptation policies (Kebede et al., 2021).

As conceptualized in Figure 9, this paralysis sets off a vicious, cascading feedback loop across the WEFE nexus. High energy requirements for pumping deeper groundwater drive up costs and greenhouse gas emissions, while the subsequent degradation of water-dependent ecosystems reduces their capacity for water purification, carbon sequestration, and microclimate stabilization, further compounding the initial water stress (Drobinski et al., 2025).

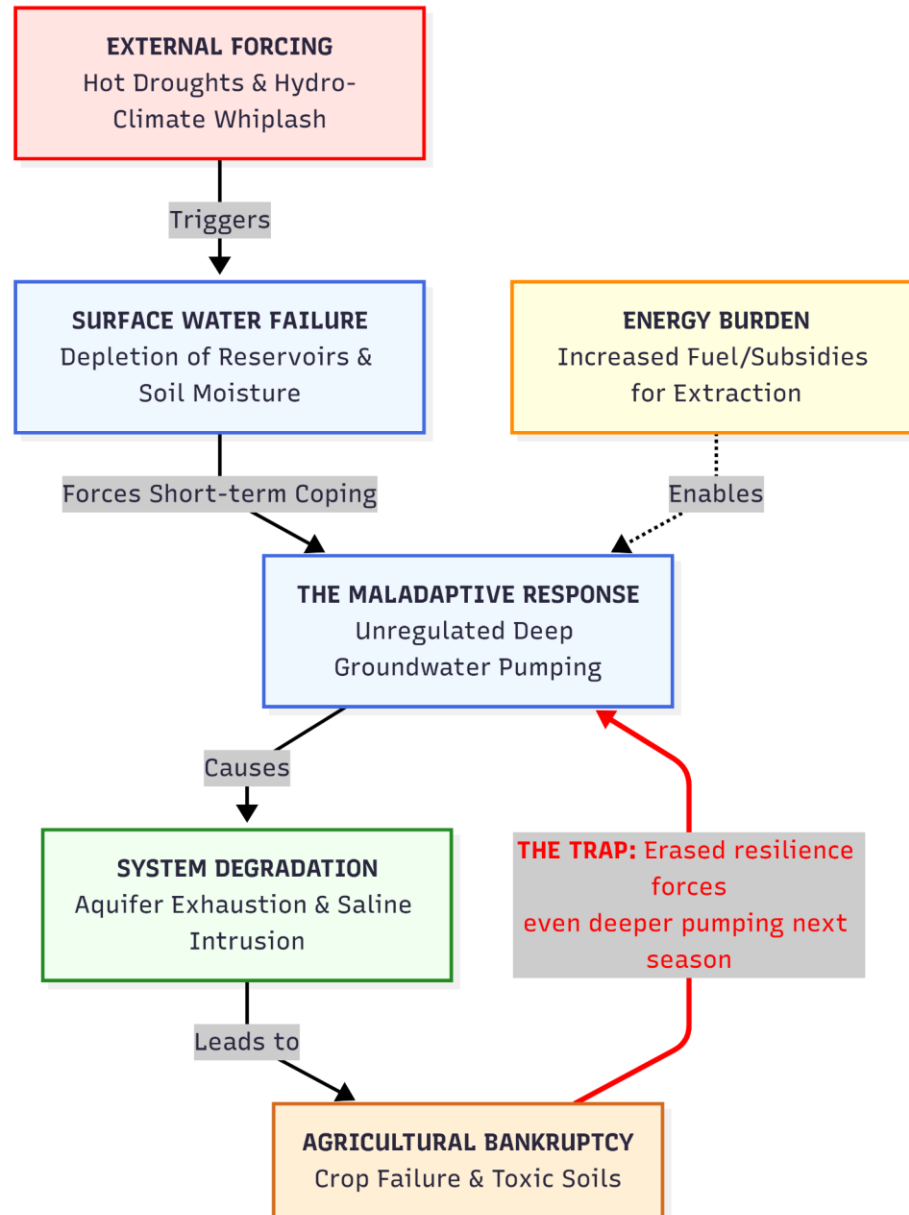


Figure 9: The WEF Nexus Maladaptation Trap. A conceptual framework illustrating the feedback loop of hydrological bankruptcy in the MESWA region. Climate-driven surface water failures (**Water**) force a heavy reliance on subsidized, unregulated groundwater pumping (**Energy**). This short-term coping mechanism drives aquifer exhaustion and soil salinization (**Ecosystems**), ultimately culminating in landscape browning and crop failure (**Food**). The trap is characterized by the feedback loop (red arrow): as resilience is eroded, the system requires exponentially greater energy and water inputs to survive subsequent climate shocks, guaranteeing the physical destruction of the region's future resource base.

The cycle begins with surface water failures (**Water**) manifested through depletion of available resources to meet demands. For example, the reductions on the Euphrates River flow are mainly triggered by upstream droughts and upstream transboundary flow reductions (Aw-Hassan et al., 2014; Voss et al., 2013). To cope with these surface deficits, national agricultural policies incentivized supplemental irrigation, which drove a 15% annual growth rate in well construction during the 1990s (Aw-Hassan et al., 2014). This policy shift forced a rigid reliance on deep groundwater extraction powered by diesel engines (Aw-Hassan et al., 2014). Because the government subsidized diesel fuel to just 20% of the global market rate—amounting to a fiscal burden of 5% of national GDP—farmers faced no cost constraint to limit extraction (**Energy**) (Aw-Hassan et al., 2014). This prolonged extraction of unconfined upper aquifers represents a literal mining of non-renewable resources, driving a drop in water table levels from historical depths of 7 to 40 meters down to 50 to 120 meters (**Ecosystems**) (Aw-Hassan et al., 2014). In northeastern Syria, this unmanaged extraction caused the complete drying of the Khabour River and accelerated soil salinization and declines in water quality (Aw-Hassan et al., 2014; Kelley et al., 2015; Yilmaz and Peker, 2013). As a result, productivity decreased due to declining water tables, and farmers could no longer sustain water-intensive strategic crops like cotton and wheat, which had been encouraged by guaranteed government purchase prices (Aw-Hassan et al., 2014). This environmental degradation ultimately resulted in widespread crop failure and the browning of the landscape (**Food**) (Kelley et al., 2015; Sukkar et al., 2024). In a final cascading step, rural households unable to maintain farming migrated to urban areas, transforming a localized resource deficit into a national socio-economic crisis (Aw-Hassan et al., 2014; Kelley et al., 2015; Yilmaz and Peker, 2013). This loop demonstrates how isolated sectoral adaptations—aiming to secure short-term food policies through subsidized energy inputs—dismantle long-term ecosystem and water security. As groundwater levels dropped, the physical energy required to lift water from deeper aquifers rose, forcing the government to increase its energy subsidy expenditures to prevent complete agricultural failure, illustrating the reinforcing feedback loop (red arrow) of the maladaptation trap (Aw-Hassan et al., 2014; Joodaki et al., 2014).

The defining characteristic of this trap is the feedback loop itself, as the system's baseline resilience is eroded and agriculture requires greater energy and water inputs merely to survive

subsequent, weaker climate shocks. This dynamic ensures that the invisible depletion will likely continue relentlessly until the absolute physical or economical limits of extraction are reached. Historical patterns of regional groundwater mining show that this trajectory rarely ends in a gradual drawdown, but rather in a "sharp decline within a short period of time" once aquifers are exhausted (Aw-Hassan et al., 2014). This drives the system toward an unmanaged agricultural collapse, resulting in the widespread abandonment of groundwater-fed farms when wells eventually run dry or when energy costs of pumping from deeper water tables become too uneconomical to sustain rural livelihoods (Perez et al., 2024).

6.3. The Erosion of Resilience and Hydrological Tipping Points

The unifying characteristic of the 2015–2026 period across the MESWA is the total erosion of hydrological resilience. In ecological and hydrological terms, resilience is defined as the capacity of a system to absorb a shock and recover to its original state. Historical data suggests that the regional water systems previously possessed a degree of elasticity; following the severe droughts of 1999–2001, satellite gravimetry (GRACE) indicates that groundwater storage exhibited a brief period of positive mass recovery during the subsequent wet years of 2003–2006 (Voss et al., 2013). However, this rebound was incomplete. The region never fully recovered from the late-1990s deficits before collapsing again into the severe 2007–2008 drought, which severely reduced the remaining groundwater buffer across large swaths of the Fertile Crescent (Kelley et al., 2015). This historical failure to fully recharge highlights the region's increasing vulnerability as it transitions into a state of chronic, thermodynamically driven depletion.

This loss of resilience has initiated a transition from temporary scarcity to permanent landscape transformation, marking the crossing of critical hydrological tipping points. We observe this in the saline tipping point in southern Iraq, where the saltwater wedge has advanced so far inland that it has fundamentally altered the soil chemistry, rendering vast tracts of arable land permanently sterile regardless of future river flow (Al-Maliki et al., 2022). Similarly, in the aquifer systems of central Iran and Afghanistan, the physical collapse of pore space due to land subsidence means that the storage capacity itself has been destroyed (Sharifi et al., 2024; Kakar et al., 2025). In Afghanistan, for instance, rapid agricultural expansion and excessive groundwater pumping have caused severe country-wide subsidence, with rates exceeding 13

cm/year in the Helmand region and nearly 78 cm over seven years in Ghazni. This rapid aquifer collapse has led to the formation of kilometer-long desiccation cracks that physically split the earth (Kakar et al., 2025). Even if internal variability were to permit a Super El Niño to provide excess rainfall, the degraded ground can barely hold it, and the runoff simply generates destructive flash floods rather than recharging the deep aquifers (FEWS NET, 2025; Kakar et al., 2025). This physical reality marks the end of the traditional drought-recovery cycle and the beginning of a new regime of hydrological hysteresis, where the system is locked into a degraded state from which climatic variability alone cannot rescue it. Ultimately, bridging the gap between food, energy, and water requires moving beyond siloed, supply-side agricultural expansions and adapting to the severe limitations of the natural water cycle within these heavily stressed regional systems (Chang et al., 2025).

7. Conclusion: Implications for Early Warning Systems

7.1. From Precipitation Deficits to Systemic Exhaustion

The contrasting hydrological outcomes of the 2015–2026 period are illustrative of the non-stationarity of hydroclimatic across the MESWA region. Contemporary drought in this corridor is no longer defined solely by precipitation deficits, but rather by a thermodynamic and anthropogenic exhaustion. Comparing the anomalous El Niño events of the last decade confirms a severe divergence between meteorological forcing and terrestrial water availability, characterized by a dual failure mechanism.

First, anticipated moisture delivery is frequently disrupted dynamically, intercepted by internal atmospheric variability and competing regional drivers. Second, and more profoundly, even when synoptic teleconnections succeed in delivering historical precipitation volumes, the moisture is thermodynamically exhausted by the extreme evaporative demand of the Hot Drought regime. This thermodynamic tax, combined with the unsustainable extraction of deep groundwater (Anthropogenic Drought), has structurally worn the region's hydrological resilience. The baseline has been lowered to such an extent that the system no longer possesses the buffering capacity to recover, pushing regional aquifers and agricultural zones past their thresholds of historical elasticity, resulting in irreversible physical degradation such as subsidence and salinization.

7.2. Recalibrating Monitoring: Pivoting to TWS and Evaporative Stress

This systemic exhaustion dictates a mandatory recalibration of regional monitoring frameworks. While ocean-basin teleconnections like ENSO remain active, their hydrological signals are increasingly masked by thermodynamic and anthropogenic forcings. Consequently, single-variable meteorological indices (such as equatorial Pacific SSTs or standalone precipitation outlooks) can no longer be solely utilized as reliable proxies for seasonal water availability in the MESWA region. As our epochal analysis demonstrated, this degradation in predictability is highly asymmetric. Because the drought-inducing signal of La Niña remains more stable, Pacific SSTs can still be reliably utilized to anticipate severe seasonal deficits. However, the historical expectation that El Niño will reliably deliver compensating wet years has deteriorated. Therefore, rather than being entirely obsolete, the historical correlations that underpinned 20th-century seasonal outlooks must be recalibrated. Operational frameworks that continue to rely on strict hydro-climatic stationarity are increasingly prone to critical forecasting errors, particularly when anticipating system recovery.

As the region approaches a state of hydrological hysteresis, Early Warning Systems (EWS) must urgently pivot from precipitation-centric forecasting to tracking the absolute limits of systemic storage and demand. To accurately anticipate agricultural shocks and systemic WEFEX nexus failures, operational forecasts must explicitly incorporate thermodynamic variables—such as the Evaporative Demand Indices and Vapor Pressure Deficit—to quantify the atmospheric tax. Crucially, this should be paired with continuous, high-resolution monitoring of subsurface TWS, such as utilizing GRACE satellite data, and localized piezometric groundwater monitoring networks.

However, operationalizing this pivot in the MESWA corridor presents significant practical challenges. The region operates under severe data scarcity, where localized piezometric networks are frequently underfunded, degraded, or entirely abandoned due to prolonged geopolitical conflict. While satellite gravimetry (e.g., GRACE and GRACE-FO) provides capabilities to track absolute subsurface depletion, relying on traditional monthly mass concentration products for localized early warning is hindered by their coarse spatial resolution. However, recent advancements in Level-1B stacked regression processing have successfully leveraged temporal

variability to improve the effective spatial resolution of GRACE data by a factor of 5 to 10, facilitating the detection of anthropogenic signatures at the watershed scale (O'Neill et al., 2026). To bridge this operational gap and bypass compromised ground networks, next-generation EWS must rely on hybrid data assimilation frameworks. By systematically integrating satellite gravimetry and high-resolution thermal remote sensing into continuous Land Surface Models (LSMs)—such as the FLDAS systems utilized in recent regional assessments—managers can temporally and spatially downscale TWS data to actionable, sub-basin resolutions. Ultimately, surviving the WEFÉ maladaptation trap requires an EWS architecture that actively synthesizes multi-sensor satellite inputs to provide near-real-time, spatially resolved tracking of the region's absolute hydrological limits.

Future resilience and early warning will depend not on anticipating when historical teleconnections will return, but on rigorously tracking the physical depletion of the landscape and managing the strict limits of what remains.

Acknowledgements

The authors gratefully acknowledge the support of the NASA Goddard Space Flight Center (GSFC) and the University of Maryland Earth System Science Interdisciplinary Center (ESSIC). We also extend our sincere appreciation to the Famine Early Warning Systems Network (FEWS NET) Science and Decision Support Teams and the U.S. Department of State for their support and invaluable guidance throughout this research.

Availability Statement

The datasets analyzed during this study are publicly accessible through their respective organizational repositories. The data that support the findings of this study are available from the corresponding author upon reasonable request. Data extraction, temporal aggregation, and statistical analyses were conducted utilizing custom Python scripts constructed using open-source libraries.

Conflict of Interest Disclosure

The authors declare there are no conflicts of interest for this manuscript.

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