

From Global Hydroclimatic Signals to Local Water-Resources Adaptation: A Critical Review of Detection, Attribution, and Scale-Dependent Evidence

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Abstract

Hydroclimatic evidence is often carried too directly from global-scale attribution studies into local water-resources decisions, despite important differences among variables, methods, and spatial scales. This critical narrative review examines how climate variability, statistical trends, detection, attribution, non-stationarity, and risk should be distinguished when interpreting changes in precipitation, drought, streamflow, floods, groundwater, and water availability. The review compares global assessments, Mediterranean studies, and selected local examples to clarify what each line of evidence can—and cannot—support in adaptation planning. Human influence on global warming is unequivocal, and increases in atmospheric evaporative demand are well supported across many regions; anthropogenic influence has also been detected in several large-scale water-cycle responses. Historical changes in precipitation, river flooding, groundwater, and local drought remain spatially heterogeneous because internal variability interacts with circulation, storage, landscape properties, abstraction, infrastructure, and demand. Statistically significant trends do not by themselves establish hydrological importance or causation, while non-significant local trends do not imply an absence of operational risk. On this basis, the review proposes a scale-aware way of matching hydroclimatic evidence with system vulnerability and the degree of commitment involved in adaptation. Low-regret and adjustable measures can address current vulnerabilities under uncertainty, whereas costly, long-lived, or difficult-to-reverse interventions require stronger local evidence and stress testing across plausible futures.

Keywords: hydroclimatic variability; trend analysis; detection and attribution; global-to-local scaling; water-resources adaptation; agricultural water management; Mediterranean hydroclimate; decision-making under uncertainty

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1. Introduction

Human influence on global warming is no longer an open scientific question. The Intergovernmental Panel on Climate Change (IPCC) concluded that human activities have unequivocally warmed the atmosphere, ocean, and land [1]. For water-resources science and management, the more difficult question is how this global conclusion translates into specific hydrological changes and management risks. Decisions depend on precipitation, evaporative demand, soil moisture, streamflow, groundwater recharge,

drought, floods, and the reliability of managed supplies, and these responses vary among variables, regions, and spatial scales [2].

The terms used to describe this evidence support different levels of inference. Climate variability describes fluctuations around a climatic state; a trend is an estimated directional change over a defined period; and statistical significance concerns compatibility with a stated null hypothesis and its assumptions. Detection asks whether a change can be distinguished from expected internal variability, whereas attribution examines the contribution of particular drivers [3,4]. A slope alone demonstrates neither persistent climatic change nor hydrological importance or anthropogenic causation. Interpretation also depends on record length and quality, variability, temporal dependence, seasonality, change points, and the selected period [5].

This difficulty increases as analysis moves from atmospheric variables to hydrological responses. Heavier precipitation need not produce a comparable flood response because runoff is modified by antecedent conditions, storage, snow processes, land cover, drainage, and regulation [6]. Streamflow and groundwater are also affected by abstraction, irrigation, reservoirs, urbanisation, and land management; groundwater pumping in particular has produced widespread depletion in many intensively used aquifers [7–9]. Anthropogenic influence has been identified in large-scale patterns of mean and extreme streamflow [10], yet European flood trends remain strongly differentiated [11]. Broad-scale coherence can therefore coexist with weak or contrasting local responses.

The Mediterranean provides a particularly informative setting. Strong warming, rising evaporative demand, seasonal water imbalance, and recurrent drought and flood episodes support its characterisation as a climate-change hotspot [12,13]. Historical precipitation trends are less uniform: their direction and statistical support depend strongly on location and analysis period, with interannual and multidecadal variability remaining prominent [14]. Higher temperatures can nevertheless intensify soil–water deficits even where precipitation trends are weak, while projections indicate increasing aridity across much of the basin.

Published evidence from north-western Crete is used as a local illustration. Records for 1960–2019 showed a slight downward tendency in the Standardized Precipitation Index (SPI), with varying statistical support, while combined hydrological and landscape information revealed marked differences in parcel-scale drought and flood proneness [15]. The example separates station-based temporal evidence from local exposure; it is not treated as an attribution study or as representative of the Mediterranean as a whole.

These distinctions determine what kinds of adaptation decisions the evidence can reasonably support. Monitoring, leakage reduction, irrigation scheduling, soil–water conservation, and drought or flood preparedness can address existing weaknesses before causal attribution is complete [16–18]. Costly, long-lived, or irreversible measures require stronger local evidence and wider testing, while adaptive pathways allow decisions to be revised as observations and system performance evolve [19].

The relevant evidence is scattered across largely separate studies on trend analysis, detection and attribution, hydrological impacts, regional assessment, and adaptation. This separation encourages three recurring errors: treating station trends as detected climate change, applying broad attribution findings directly to individual basins, and using uncertain local projections either to delay action or to justify inflexible investment.

This review addresses four questions:

1. How should climate variability, trends, statistical significance, detection, attribution, non-stationarity, and risk be distinguished in hydroclimatic research?
2. Why does the strength of evidence differ among variables and spatial scales?
3. Which conclusions are supported by global, Mediterranean, and selected local evidence, and where do important uncertainties remain?

4. How can different levels of evidence inform proportionate water-resources adaptation?

These questions connect four parts of the same reasoning chain: what changed, how strongly the available record supports that conclusion, what may have caused the change, and why it matters for a particular decision. Building on this chain, the review develops a scale-aware decision framework organised around three considerations: the strength and spatial relevance of the hydroclimatic evidence, the vulnerability of the water system and the consequences of failure, and the lifetime and reversibility of the proposed response. The framework is not intended as a predictive model or a prescriptive decision-support tool. Rather, it provides a structured way of judging whether the available evidence is sufficient for low-regret action, a staged adaptive pathway, or a longer-lived and more difficult-to-reverse commitment. Section 8 develops this decision logic.

2. Review Scope, Literature Search, and Analytical Approach

The aim was not simply to catalogue reported hydroclimatic changes, but to assess what type of conclusion each line of evidence can reasonably support. The relevant literature spans climate detection and attribution, statistical trend analysis, hydrology, drought and flood research, groundwater, agricultural water management, and decision-making under uncertainty. These fields often focus on different variables, spatial scales, and standards of inference. A critical narrative approach was therefore used to examine how the evidence should be interpreted and what it can realistically contribute to water-resources decisions, rather than simply compiling the trends reported in individual studies.

The literature search was conducted mainly through the Web of Science Core Collection and Scopus. Google Scholar was used for targeted supplementary searches and for backward and forward citation tracking. It was also used to identify foundational methodological papers and recent studies relevant to particular regional or local examples. Major assessments and technical guidance from the IPCC, World Meteorological Organization (WMO), and Mediterranean Experts on Climate and Environmental Change (MedECC) were included when they provided widely accepted definitions or broad syntheses of the evidence. No lower publication-date limit was imposed. The search was last updated in June 2026 and covered literature from foundational methodological studies published in 1945 to peer-reviewed research available at that time.

The search was organised around four broad themes: hydroclimatic trends and statistical methods; detection and attribution; hydrological impacts across spatial scales; and water-resources adaptation under uncertainty. Representative search terms included precipitation, drought, flood, streamflow, groundwater, soil moisture, trend analysis, Mann–Kendall, Sen’s slope, change point, non-stationarity, internal variability, anthropogenic attribution, Mediterranean, basin, catchment, aquifer, robust decision-making, decision scaling, adaptive pathways, and maladaptation. These terms were used in different combinations and refined as recurring concepts, influential studies, and relevant citation pathways emerged.

The synthesis focused on studies that addressed one or more of the review questions, clarified an important methodological distinction, or showed how broad climatic signals are modified by hydrological processes, water use, infrastructure, and local vulnerability. Priority was given to major assessments, foundational methodological contributions, multi-region analyses, and recent peer-reviewed studies that clearly reported their data, methods, spatial scale, and treatment of uncertainty. Studies were generally not retained when the variable or analysis period was insufficiently defined, when the evidence did not support the causal or spatial claim being made, or when a local case study repeated a

point already demonstrated more clearly elsewhere. Local examples were selected for their explanatory value rather than as statistically representative evidence.

Studies were compared in terms of the type of claim they supported, the hydroclimatic variable and spatial scale examined, and the extent to which climatic influences could be distinguished from abstraction, infrastructure, land management, exposure, and vulnerability. Global studies provided the broad physical and attributional context; Mediterranean research was used to examine regional heterogeneity; and selected local studies illustrated how site-specific processes shape exposure and realised impacts. The north-western Crete study serves only this illustrative purpose. No meta-analysis was attempted because the literature differed substantially in variables, periods, statistical methods, model structures, and spatial units. The synthesis instead focused on convergence across independent lines of evidence, the assumptions underlying each conclusion, and the conditions under which that conclusion remains valid.

3. Conceptual Framework and Terminological Boundaries

Hydroclimatic studies may describe observed behaviour, test for temporal change, investigate its causes, or assess its consequences. Variability, anomaly, trend, detection, attribution, impact, and risk refer to different stages of this reasoning.

3.1. Variability, Anomalies, and Climatic Forcing

Climate variability describes departures from a climatic mean across temporal and spatial scales beyond individual weather events [20]. In precipitation, streamflow, soil moisture, and drought records, it may persist from seasons to decades and dominate the observed record. A climatic anomaly is the difference from a selected reference, usually a climatological mean. Its magnitude depends on the baseline, so the same year may appear wetter or drier against different 30-year periods [21]. An anomaly provides context but does not establish climatic change.

Internal variability refers to fluctuations generated within the climate system under constant or periodically varying external forcing, such as the annual cycle [20]. It may reinforce, obscure, or temporarily oppose a forced response, and its influence is generally greater for regional precipitation and circulation than for temperature [22,23]. Natural climate change also includes responses to volcanic and solar forcing, while anthropogenic change is driven mainly by greenhouse gases, aerosols, and land-use change. Human influence on global warming is unequivocal [1,4], although natural variability continues within that altered background.

3.2. Trends, Change Points, and Non-Stationarity

A trend is an estimated directional change over a specified period. Its magnitude, support, and sometimes sign depend on the variable, season, method, and selected years [5]; reporting should therefore include location, period, rate, and uncertainty. Non-stationarity refers to changing statistical properties through time and has important implications for water planning [24]. It does not identify cause: climatic forcing, abstraction, reservoir operation, urbanisation, land-cover change, or measurement practices may all contribute. A change point marks a shift in a property such as the mean, variance, or frequency of extremes [25]. It can occur without a monotonic trend, while a gradual trend may have no identifiable breakpoint. A regime shift usually denotes a relatively abrupt and persistent transition between states [26].

3.3. Detection and Attribution

Detection asks whether an observed change is unlikely to arise from internal variability alone [4,20], a stronger requirement than significance under a conventional trend-test null hypothesis. Attribution estimates the contribution of particular drivers against plausible alternatives [4]. For extreme events, it usually concerns changes in probability or intensity rather than a single exclusive cause [27]. Hydrological attribution must additionally account for soils, vegetation, geology, storage, infrastructure, and water use. Changes in streamflow or groundwater may reflect climatic inputs, evapotranspiration, abstraction, regulation, land-cover change, or interactions among these influences [7,28].

3.4. From Hazard to Risk

Hazard is a physical event or trend with potential to cause harm; exposure concerns the people, ecosystems, infrastructure, livelihoods, or assets in harm's way; vulnerability describes their predisposition to adverse effects; and risk arises from their interaction [29].

A precipitation deficit may be manageable in a diversified, well-stored system but severe in an over-allocated basin. Likewise, intense precipitation becomes damaging flooding only through the interaction of runoff generation, flow pathways, exposure, and vulnerability. Risk can rise without a climatic trend through urban growth or increasing demand, and decline despite a changing hazard where adaptation reduces exposure or vulnerability.

Throughout this review, variability and anomalies describe climatic behaviour; trends and other forms of non-stationarity characterise temporal change; detection and attribution address evidence and causality; and risk links hydroclimatic signals with consequences. Figure 1 summarises this evidential progression and its spatial context, while Table 1 clarifies what each concept can and cannot support.

Table 1. Key evidential concepts in hydroclimatic research and the claims they can and cannot support. Source: Author's synthesis based on [4,20,29].

Concept	What it Means	What it Can Support	What it Cannot Support
Climate variability	Natural fluctuations around a climatic state across seasonal to multidecadal time scales.	Characterisation of baseline variability, extremes, and planning ranges.	Directional change, causation, or future projections.
Trend	An estimated directional change in a variable over a defined period.	Description of change in the observed record and input to risk or adaptation analysis.	By itself, statistical support, detection, or attribution.
Statistical support	Compatibility of the observed trend with a null hypothesis under stated data and model assumptions.	Assessment of sampling uncertainty for a specified method and record.	Hydrological importance, practical relevance, or causation.
Detection	Evidence that an observed change is unlikely to be explained by the estimated range of internal variability alone.	A conclusion that the observed change exceeds the estimated variability background at the scale assessed.	Attribution to a specific driver or automatic local relevance.
Attribution	Assessment of the contribution of specified drivers against plausible alternatives.	Causal interpretation at the scale and for the variables examined.	An exact local magnitude for every site or impact.
Non-stationarity	Change through time in statistical properties such as the mean, variance, persistence, or extremes.	The need for time-varying analysis, monitoring, and adaptive management.	The direction or cause of change, or a unique future outcome.

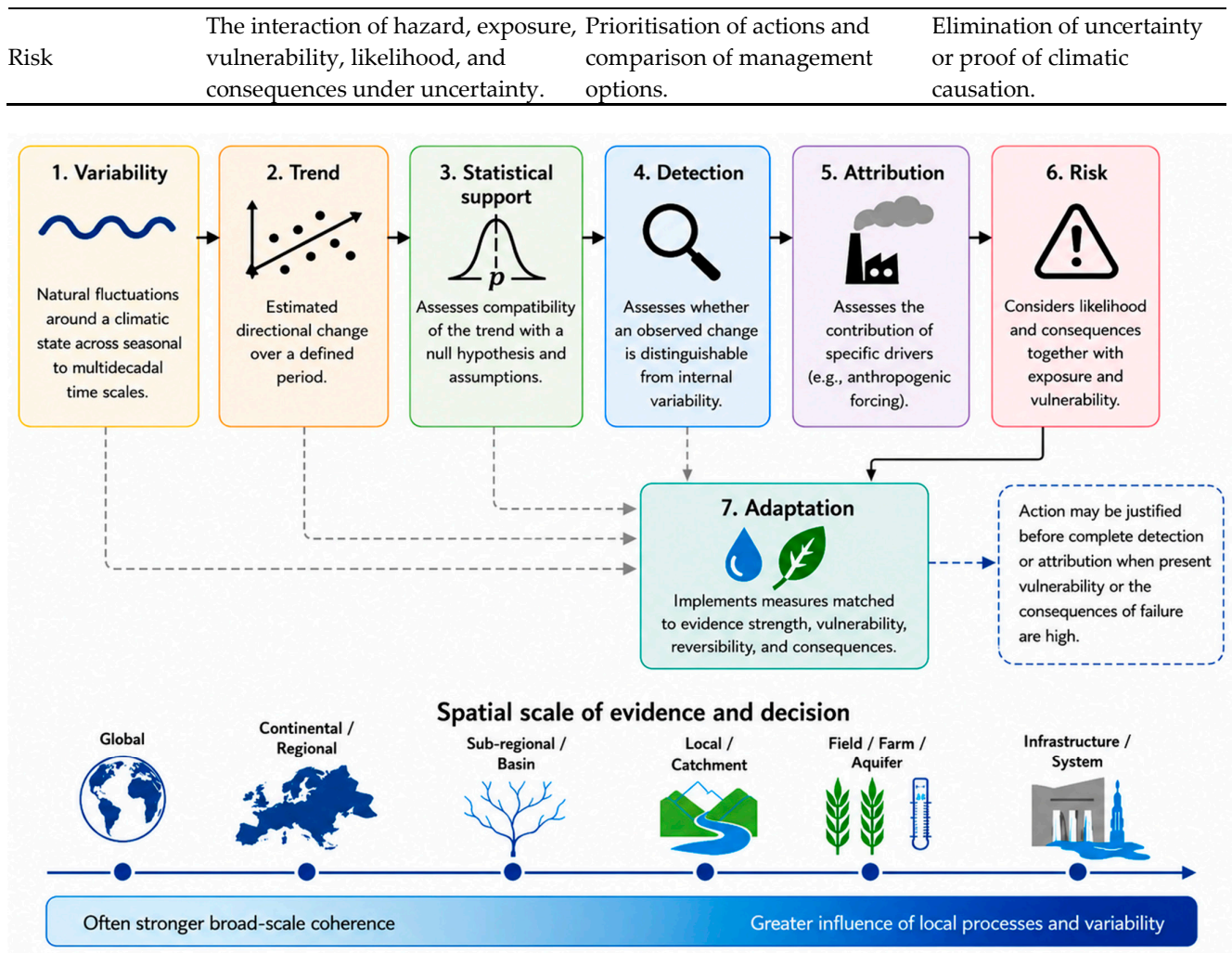


Figure 1. Evidential steps from hydroclimatic variability to adaptation and their relation to spatial scale. The sequence distinguishes descriptive, statistical, causal, risk, and decision-oriented claims. Solid black arrows indicate the principal evidential progression from variability to risk and the subsequent link to adaptation. Grey dashed arrows indicate that adaptation may also be initiated from earlier evidential stages when present vulnerability or the consequences of failure justify action before complete detection or attribution. The blue dashed arrow links the adaptation step to this qualification, while the lower solid blue arrow indicates the transition from broad-scale coherence towards the increasing influence of local processes and variability. Note: For many hydroclimatic variables, confidence generally decreases as the analysis moves from broad, large-scale signals towards local impacts, although this pattern is not uniform and detailed local observations may sometimes provide stronger constraints. In the schematic, p denotes the p -value associated with the stated statistical test. Source: Author's conceptualisation based on the definitions and evidential distinctions in [4,20,29].

4. From Observed Change to Statistically Supported Trends

Trend analysis is central to hydroclimatic research, yet its interpretation is not always straightforward. An estimated slope, the statistical evidence supporting it, and its relevance to water management describe different aspects of a record. Each depends on the method used, the quality and structure of the data, and the period and spatial domain examined. In this review, the term statistical support is used more broadly than the binary

label “statistically significant”. It also encompasses effect size, uncertainty, data quality, and the assumptions underlying the specified test.

4.1. What a Trend Test Shows

Once a trend has been defined for a specific period, the next question is how strongly the available record supports it. The Mann–Kendall test is widely used for precipitation, streamflow, drought indices, groundwater levels, and related hydrometeorological variables [30–32]. It does not require normally distributed data and is comparatively resistant to individual extremes [33]. It assesses whether observations tend to increase or decrease monotonically through time. A significant Mann–Kendall result implies neither linear change nor continuation beyond the analysed period. Rapid increase followed by stabilisation may retain a monotonic signal, whereas a rise followed by decline may show little net trend despite substantial internal change. Visual inspection and, where appropriate, change-point or nonlinear analysis remain necessary. Direction should be accompanied by magnitude. Sen’s slope, based on the median of pairwise slopes, is less sensitive to outliers than ordinary least squares [34]. Trends with similar p -values can differ greatly in physical size and operational consequence.

4.2. Statistical Evidence and Hydrological Importance

A significance test measures compatibility with a specified null hypothesis and its assumptions; it gives neither the probability that the null is true nor the practical importance of the change [35]. Treating $p = 0.049$ and $p = 0.051$ as qualitatively different is therefore misleading when slopes and uncertainty ranges are nearly identical. Interpretation should include effect size, confidence intervals, data quality, physical plausibility, and system sensitivity. A statistically supported trend may have little operational consequence if its magnitude is small compared with natural variability, reservoir capacity, aquifer storage, or existing safety margins. A less strongly supported trend may still matter where the system is already close to a supply, ecological, or infrastructure threshold. A non-significant result is not evidence of no change. It means that the available record provides insufficient evidence against the stated null hypothesis, perhaps because the trend is weak, the record short or variable, data quality limited, or the change non-monotonic.

4.3. Record Length and the Choice of Analysis Period

Trend-detection power depends on change magnitude relative to variability and temporal dependence. Longer records usually help, but temperature trends often emerge more clearly than precipitation, drought, or streamflow trends because the latter contain stronger interannual and multidecadal variability [22,23]. Simulation studies show that rank-based tests are affected by sample size, variance, persistence, trend magnitude, and the statistical form of the series [30]. The difficulty is greater for extremes, where annual-maximum or annual-minimum records may contain only one observation per year. Several decades of data may therefore still provide limited information about rare-event change. Results also depend on the observation window. UK peak-flow trends varied with the selected period [36], Canadian hydrological records showed period-dependent regional patterns [32], and long Mediterranean precipitation records demonstrate how multidecadal variability shapes shorter trends [14]. Across these examples, adding or removing a decade can alter the slope, its support, or occasionally its sign.

This sensitivity does not make every trend arbitrary. It shows that temporal stability should be tested rather than assumed. Moving-window estimates, nested periods, and comparisons among physically defensible start dates can reveal whether the result is persistent or depends strongly on a particular sequence of wet and dry years.

4.4. Temporal Dependence, Seasonality, and Non-Monotonic Change

Hydroclimatic observations are rarely independent through time. Wet or dry conditions may persist across years, groundwater and reservoir storage introduce memory, and soil-moisture anomalies can outlast the event that produced them. Positive serial correlation reduces the effective amount of independent information and may inflate the apparent significance of a trend [31,37].

Several approaches have been proposed to account for temporal dependence in trend analysis, including effective sample-size adjustment, variance correction, resampling, and prewhitening. Conventional prewhitening removes estimated serial correlation before trend testing, but it may also weaken a genuine trend because the calculated correlation can include part of the underlying change [38]. Trend-free prewhitening and modified variance methods were developed in response, although their performance still depends on sample length and persistence [31,37,38].

No single correction is preferable in every case. The residual dependence after trend removal should be examined, and sensitive results should be tested with more than one reasonable method. Agreement among approaches is more informative than reliance on one adjusted p -value.

Seasonality raises a related issue. Annual aggregation may conceal contrasting seasonal tendencies, whereas direct testing of monthly data can violate the assumptions of the analysis if the seasonal cycle is ignored. The seasonal Kendall test evaluates trends within comparable seasons before combining the results, and extensions allow serial dependence within seasons to be considered [39,40]. Separate seasonal analyses may be more useful when water availability depends on precipitation timing, snowmelt, dry-season length, or irrigation demand.

Important changes are not always monotonic. Precipitation concentration, dry-spell duration, flood timing, persistence, or variance may change without a trend in the annual mean. Change-point and regime-shift methods can identify abrupt or persistent transitions [25,26], but climatic interpretation should follow checks for station relocation, instrumentation, processing, reservoir construction, abstraction, and land-use change, supported where possible by station metadata and homogeneity assessment [5,21].

4.5. Multiple Testing and Regional Interpretation

Regional studies often analyse many stations, grid cells, variables, seasons, or indices. At a nominal 5% significance level, some results will appear significant by chance when many tests are performed. Spatial correlation makes simple counting even less reliable because neighbouring locations do not provide independent evidence. Counting stations with $p < 0.05$ is therefore insufficient. Field-significance methods test whether the collective pattern exceeds a regional null while accounting for dependence [41]; resampling can preserve spatial structure, and false-discovery-rate procedures limit the expected proportion of false rejections [42].

A common trend direction across several stations may indicate a spatially coherent but weak signal, particularly where individual records have low statistical power. It may also reflect shared multidecadal variability. Mediterranean precipitation records provide an example of broad directional patterns that remain strongly period-dependent [14], while UK peak-flow analyses show how the apparent regional signal can change with the selected observation window [36]. Regional interpretation is strongest when direction, magnitude, uncertainty, spatial coherence, and physical understanding support the same conclusion. At minimum, trend studies should report period, completeness and homogeneity, slope and uncertainty, treatment of seasonality and temporal dependence, and sensitivity to alternative windows. Multi-site analyses should also address spatial dependence and multiple testing, supported by graphs that reveal features hidden by a

single statistic. Trend analysis describes how a record evolved under a chosen analytical framework. Even long precipitation records may remain strongly influenced by natural variability [43]; deciding whether change exceeds that variability and identifying its causes requires detection and attribution.

5. Detection, Attribution, and Scale-Dependent Confidence

A statistically supported trend does not establish that an observed hydroclimatic change exceeds natural variability or identify its causes. Detection and attribution require additional evidence: an estimate of the variability that could arise without the forcing under investigation, a physically credible expected response, and consideration of competing climatic and non-climatic explanations. Examples include attribution of global mean and extreme streamflow patterns [10], European seasonal precipitation changes [44], European soil-moisture drought [45], and flood trends in Mediterranean basins [46]. Moving from atmospheric signals to hydrological responses and local impacts makes attribution increasingly demanding.

5.1. Detection Beyond Trend Significance

Unlike a conventional trend test, detection requires an estimate of the variability that the climate system could generate without the forcing of interest [4,47]. A Mann–Kendall test evaluates the temporal ordering of an observed series under particular assumptions; it does not represent the full range of internally generated climate variability. Detection studies commonly compare observations with ensembles under anthropogenic and natural forcing. Optimal fingerprinting estimates the amplitude of an expected spatial or temporal response pattern [47,48]; detection is supported when that contribution differs from zero. Attribution further requires consistency with the proposed forcing and exclusion of more plausible alternatives.

The distinction is particularly important for precipitation and hydrological variables, where internal variability and local controls are strong. Temperature responds to radiative forcing through a relatively coherent large-scale signal. Precipitation, by contrast, is strongly affected by circulation, storm tracks, convection, and topography, and internal variability can obscure or temporarily oppose a forced response at regional and local scales [22,23]. The heterogeneous Mediterranean station record [14] and the seasonally differentiated European attribution results [44] illustrate this scale dependence. A station trend may therefore be genuine and operationally relevant without showing that the observed change lies outside the expected range of natural variability.

5.2. Attribution as a Comparison Among Causes

Attribution is a structured comparison among causes [4,47]. Support is stronger when the observed response matches a driver's expected influence, is difficult to reproduce without it, and is not explained more adequately by alternatives. Language should follow the evidence: "consistent with" is weaker than demonstrating a contribution, and neither necessarily identifies the dominant cause.

Counterfactual reasoning provides the underlying logic by asking how the outcome would have differed without the forcing or intervention of interest [49]. Since this alternative state cannot be observed, it must be estimated through models, observations, and physical understanding. The resulting inference depends on the quality of the observations, representation of internal variability, model adequacy, and treatment of other drivers.

5.3. Extreme Events and Storyline Approaches

Extreme-event attribution assesses whether anthropogenic influence changed the probability or intensity of a defined event or class of events [27,49]. It rarely implies that climate change produced a particular drought, flood, or storm by itself. Instead, simulations representing the observed climate are compared with counterfactual simulations in which anthropogenic influence is removed or reduced. For example, such an approach was used to estimate the anthropogenic contribution to flood risk in England and Wales in autumn 2000 [50]. Storyline approaches address a related but different question by examining how a physically plausible event sequence may unfold under specified conditions [51]. The result depends on how the event is defined. Drought may refer to precipitation deficit, soil-moisture conditions, streamflow, reservoir storage, or compound heat and water stress. Spatial extent, season, duration, and severity threshold can also affect the estimated change in probability. Different studies of the same historical episode may consequently address different aspects of the event.

Confidence is generally higher when the physical link to warming is direct and well represented in models. It is typically greater for heat extremes than for local convective precipitation, individual river floods, or hydrological droughts affected by water management [27]. In the latter cases, the causal pathway includes several intermediate processes that can alter the final response. Storyline approaches instead explore how an observed or plausible event sequence changes under alternative thermodynamic, hydrological, or land-surface conditions [51]. Their assumptions and process chains are transparent, but they do not necessarily quantify the sequence's probability. Storylines and probabilistic attribution are therefore complementary.

5.4. Hydrological Attribution in Managed Systems

Hydrological variables integrate climatic inputs with soils, geology, vegetation, storage, infrastructure, and water use. Changes in streamflow may reflect precipitation, snowmelt, evapotranspiration, groundwater exchange, reservoir operation, abstraction, drainage, urbanisation, or land-cover change. These influences may act together and may either reinforce or offset one another. Flood attribution illustrates the difficulty. An observed increase in heavy precipitation may offer a plausible explanation for higher peak streamflow, but a causal claim also requires evidence that the precipitation change can reproduce the flood response and that competing explanations are less consistent with the observations. Reviews and regional studies show why explicit comparison of climatic and non-climatic hypotheses is needed [28,46]. Groundwater attribution presents the same problem because recharge, pumping, irrigation return flows, and aquifer properties may all contribute to the observed response [7].

Hydrological drought presents a related problem. In managed basins, it cannot always be interpreted as the direct propagation of a precipitation deficit. Irrigation, abstraction, reservoir operations, interbasin transfers, and land management may intensify, delay, redistribute, or partly alleviate water shortages [52]. Human activity can alter both the physical hazard and the vulnerability of the system. Separating climate-induced drought from demand-driven scarcity requires a defined reference condition and adequate information on withdrawals, storage, and operating rules. The same challenge applies to groundwater. Changes in groundwater levels or groundwater discharge may reflect variations in recharge, pumping, land use, irrigation return flows, and aquifer management. A climatic attribution based only on an observed downward trend would therefore be incomplete unless these other influences were examined.

5.5. Confidence from Global Forcing to Local Impact

Figure 2 traces the pathway from anthropogenic forcing to water-related impacts and identifies the main sources of uncertainty introduced at each stage. Each transition introduces processes that can alter the strength, timing, or even the direction of the signal. Regional circulation affects precipitation; topography redistributes precipitation; soil and subsurface storage regulate runoff and recharge; infrastructure modifies water movement and availability; and exposure and vulnerability shape the consequences [2,3,29,53].

The level of confidence is not constant along this chain. Human influence may be clearly detected in regional warming, reasonably supported in atmospheric evaporative demand, less easily separated from variability in local precipitation or soil moisture, and difficult to quantify in crop loss because irrigation, soils, crop management, and economic conditions also intervene. Lower confidence in the final impact does not weaken the evidence for the earlier links; it reflects the greater number of processes and possible explanations involved. Broad spatial analyses may improve detection because a forced pattern can emerge from the collective behaviour of many locations. Such findings do not require identical trends at every gauge, nor do they establish the dominant driver in each individual basin.

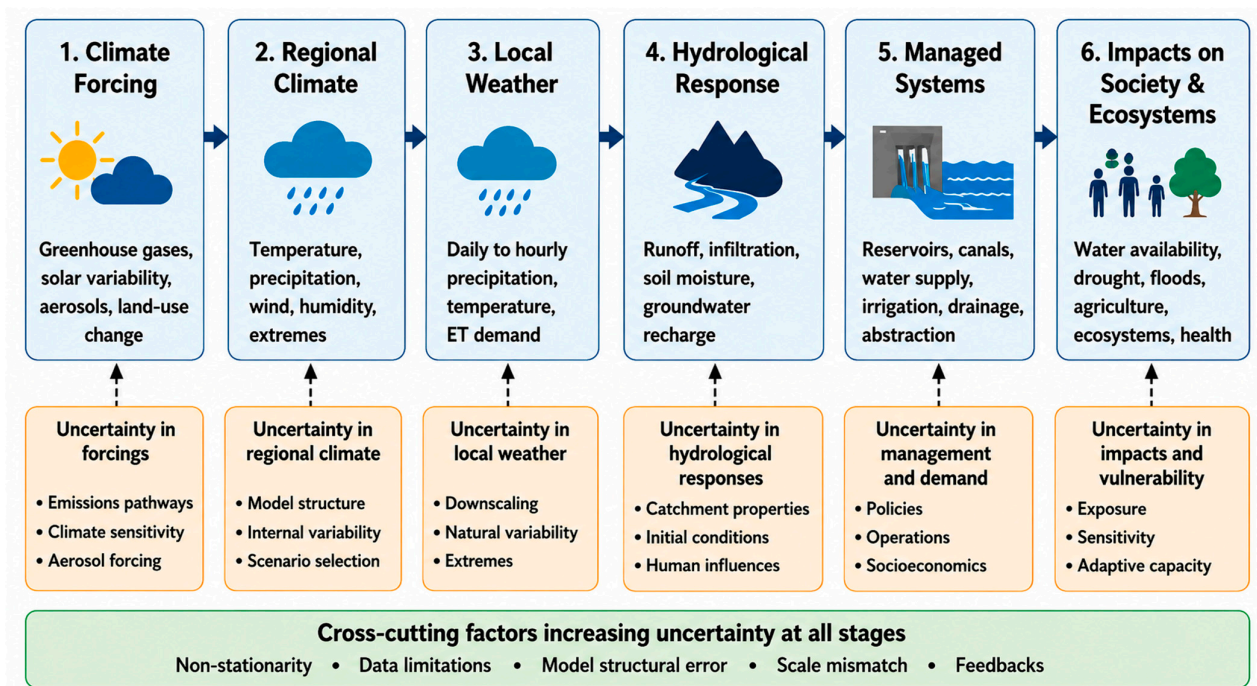


Figure 2. Hydroclimatic impact chain from climate forcing to societal and ecosystem consequences. Uncertainty is introduced through regional climate, local weather, hydrological response, water management, exposure, and vulnerability; non-stationarity, data limitations, model structural error, scale mismatch, and feedbacks operate across stages. Note: The impact chain is not strictly linear. Feedbacks may occur between stages; for example, land-use change, water-management decisions, and ecosystem responses can influence local climate and hydrological processes. ET denotes evapotranspiration. Source: Author's conceptualisation based on [2,3,29,53].

Local evidence may nevertheless be well constrained where detailed observations, process knowledge, water balances, and records of intervention are available. The adequacy of the evidence matters more than scale alone. A trend-only local study should report tendency and uncertainty; direct anthropogenic attribution requires counterfactual modelling, large-scale fingerprints, internal-variability estimates, and assessment of

alternatives [4,47,48]. Local findings may still matter operationally even when the relative contributions of different causes remain uncertain. Keeping trend, detection, and attribution claims distinct allows broad climate evidence to inform local decisions without assigning unsupported certainty or spatial specificity [10,53].

6. Global and Regional Evidence Across Hydroclimatic Variables

Hydroclimatic change is neither uniform across the water cycle nor equally well constrained. Evidence is strongest for warming and associated energy-balance changes. Heavy precipitation has intensified across many land regions, and anthropogenic influence has been detected in several large-scale water-cycle responses [1,2,54]. Mean precipitation, drought, runoff, groundwater, and flooding vary more regionally because they depend strongly on circulation, storage, landscape, and water management.

6.1. Warming, Evaporative Demand, and Water-Cycle Responses

Higher temperatures alter atmospheric moisture, snow accumulation and melt, evaporative demand, soil–water loss, vegetation water use, and seasonal runoff [2,54]. These processes can increase water stress even where precipitation shows little or statistically uncertain change. A warmer atmosphere can retain more water vapour and favour heavier precipitation when moisture and dynamics are suitable. Observations and models show increases in the intensity and frequency of heavy precipitation across many land regions, with an anthropogenic contribution [54,55], although local station signals may be obscured by convective variability, topography, sparse networks, and short records. Human influence has also been identified in streamflow seasonality [56]. These large-scale findings do not imply uniform change across snow-dominated, humid, semiarid, regulated, or groundwater-fed basins.

6.2. Mediterranean Warming and Precipitation Change

Mediterranean warming is well established. Land temperatures have risen faster than the global average, especially during summer, and further amplification is projected [12,57,58]. Rising atmospheric evaporative demand is contributing to greater climatic aridity and increasing pressure on soils, ecosystems, agriculture, and water-supply systems. Precipitation presents a less uniform historical picture. Climate-model ensembles project declining precipitation across much of the Mediterranean during the twenty-first century, particularly under higher-emission pathways and during the warm season [12,57,58]. Changes in storm tracks, atmospheric circulation, land–atmosphere feedbacks, and thermodynamic conditions contribute to this projected response [59].

Observational records show greater spatial and temporal diversity. An analysis of more than 23,000 Mediterranean stations found strong dependence on location and study period, with interannual and multidecadal variability dominating much of the historical record [14]. Positive and negative tendencies occurred across many stations, but statistically significant trends remained uncommon, while atmospheric circulation explained a substantial share of the observed variability. Historical heterogeneity and projected drying address different questions: observations sample one realised sequence of forcing and variability, whereas projections estimate the response to continued warming. Weak station trends do not invalidate regional projections, but projections cannot establish that drying has already been detected everywhere.

Anthropogenic influence on European seasonal precipitation also varies by region and season [44]. Mean and extreme precipitation should be separated: annual totals may change little while precipitation becomes concentrated into heavier events or longer dry intervals. Models also suggest increasing precipitation variability in a warmer climate [60].

6.3. Drought as a Multidimensional Process

Drought conclusions depend on the variable and index used. Meteorological drought usually refers to precipitation deficit, agricultural and ecological drought to soil–water availability and plant stress, and hydrological drought to reduced streamflow, reservoir inflow, groundwater, or stored water. These forms differ in onset, persistence, and recovery.

The Mediterranean has experienced severe droughts throughout historical and reconstructed periods. Tree-ring records extending over several centuries reveal pronounced natural variability in drought frequency, duration, and spatial extent [61]. Recent droughts should be interpreted against this background rather than assumed to represent a uniform new climatic regime. Warming is nevertheless altering the conditions under which precipitation deficits develop. Human influence has increased the likelihood of Mediterranean meteorological drought years [62]. Separately, anthropogenic warming has exacerbated European soil-moisture droughts [45], even though historical Mediterranean precipitation trends remain spatially heterogeneous [14]. Higher temperature and evaporative demand accelerate soil–water loss and vegetation stress [45].

The choice of drought index can consequently alter the apparent trend. SPI describes precipitation anomalies, while the Standardized Precipitation Evapotranspiration Index (SPEI) also incorporates atmospheric evaporative demand. Under warming, the two may show increasingly different behaviour because they represent different processes. The original SPEI formulation and subsequent methodological work also show that results depend on the method used to estimate atmospheric evaporative demand and to fit the underlying probability distribution [63,64]. Neither index is universally preferable; the choice should follow the process and decision being examined. As drought propagates through managed systems, reservoir and aquifer storage, soils, snow, irrigation demand, and operating rules may delay, amplify, or buffer a meteorological deficit. Claims of increasing drought should specify type, index, period, season, and scale.

6.4. Intense Precipitation and Flood Response

Intense precipitation and river flooding are linked but not equivalent. Flood response depends on event duration and extent, antecedent soil moisture, snowmelt, catchment structure, land cover, regulation, and floodplain connectivity. Short-duration intensification may raise flash-flood risk without a comparable trend in large-river annual maxima. European flood magnitudes have increased in some regions and decreased in others [11], while flood timing has shifted across substantial parts of the continent [65]. Differences reflect regional combinations of winter precipitation, snow processes, soil conditions, circulation, and catchment storage. Confidence in intensifying heavy precipitation can thus be greater than confidence in the direction of local river-flood change.

Mediterranean basin studies have likewise identified both increasing and decreasing flood trends, with precipitation alone unable to explain the observed patterns [46]. Dry antecedent conditions can reduce runoff from some events, whereas saturated soils, urban surfaces, or steep topography can amplify it. Southern French basins show that flood timing and generating mechanisms can change without a monotonic magnitude trend. Earlier and more seasonally concentrated floods were associated with changes in circulation and lower antecedent soil moisture; the latter reduced runoff coefficients and helped explain why stronger event precipitation did not translate into a monotonic flood-magnitude trend [66]. Flood risk may still rise in the absence of a clear streamflow trend. Urban development, infrastructure expansion, channel alteration, and occupation of flood-prone land can increase exposure and losses. Precipitation, hydrological hazard, exposure, and vulnerability must be examined separately.

6.5. Groundwater and Managed Water Availability

Aquifers can buffer short-term precipitation deficits, but groundwater response depends on geology, recharge pathways, unsaturated-zone thickness, storage, and pumping [7]. Global model estimates show a very wide range of response times: nearly half of global groundwater recharge flux is associated with systems that may re-equilibrate within about 100 years, whereas the global median groundwater response time is approximately 5700 years [67]. Monitoring records may therefore capture only part of the adjustment to climatic and management change. Recharge is often episodic in dry regions, with a small number of intense precipitation events contributing disproportionately. More intense precipitation does not necessarily reduce recharge, although rapid runoff, soil sealing, low infiltration capacity, and short event duration may limit the fraction reaching the aquifer. The outcome varies among hydrogeological settings. Groundwater decline must be interpreted alongside abstraction. Global assessments show widespread and often accelerating declines, particularly in intensively irrigated dry regions [8]. Pumping is frequently a major pressure, while warming can increase abstraction by raising irrigation demand as surface water and replenishment become constrained.

Across the Mediterranean, climate-related pressures interact with irrigation, urban growth, tourism, ecosystem requirements, and uneven access to infrastructure and storage [13,57,68]. Seasonal scarcity is particularly severe in the southern and eastern Mediterranean, but islands and irrigated areas in the north also face substantial demand–supply imbalances. At larger scales, human influence has also been detected in observed changes in dry-season water availability, although the local expression remains conditioned by storage and water use [69]. In Greece, national-scale evidence similarly points to marked spatial inequalities in water availability and to the importance of agricultural adaptation for water-resources management, particularly in relation to drought, flooding, soil erosion, and water-quality pressures [70]. Regional models generally project lower runoff and recharge, longer dry periods, and stronger competition, although magnitudes vary with emissions, climate and hydrological models, downscaling, evapotranspiration, and demand assumptions [57,71]. For planning, the outcome range is more informative than a single ensemble mean.

6.6. Implications for Adaptation

Across the reviewed literature, evidence is strongest for warming and rising atmospheric evaporative demand, with broad support for changes in heavy precipitation and selected large-scale hydrological responses. Examples include detected changes in European seasonal precipitation [44], contrasting flood trends and processes in Mediterranean basins [46,66], and widespread groundwater decline in intensively irrigated dry regions [8]. Local precipitation, flood, recharge, and managed-supply responses remain more heterogeneous because climatic variability is filtered through catchment and aquifer properties, infrastructure, abstraction, and demand. Section 7 uses cross-scale examples to show how these differences affect local interpretation, while Section 8 links them to adaptation choices.

7. Evidence Across Scales: From Global Exposure to Parcel-Level Impacts

Global and regional assessments describe changing water-related pressures but cannot by themselves locate the most consequential impacts within a basin, farming region, or irrigation system. Local decisions also require evidence on soils, drainage, water access, land management, infrastructure, and crop characteristics. To show how the

meaning and practical relevance of hydroclimatic evidence change with scale, Section 7 draws on three examples: projected global cropland exposure, observed field-level yield effects, and parcel-scale drought and flood proneness. The examples are illustrative rather than directly comparable or globally representative.

7.1. Indicator Choice and Global Cropland Exposure

A global study assessed future cropland exposure to concurrent and transitional droughts using SPI and SPEI under the Shared Socioeconomic Pathway scenarios SSP2-4.5 and SSP5-8.5 [72]. SPI indicated modest changes in some categories but larger increases in extreme drought exposure, especially under the higher-emission pathway. Projected exposure increased more strongly when assessed with SPEI, which also accounts for atmospheric evaporative demand.

The global analysis also revealed strong geographical and socioeconomic contrasts [72]. It could not, however, resolve actual yield losses, irrigation reliability, soil limitations, or farm-level adaptive capacity. The example shows that even a broad estimate of drought exposure depends on the indicator, scenario, cropland distribution, and socioeconomic setting.

7.2. Field-Level Effects of Drought and Intense Precipitation

At field scale, climatic exposure and realised impact can be separated more clearly. Mulders et al. analysed potato-production data from sandy soils in the southern Netherlands during 2015–2020, using a matching approach to separate weather-related effects from differences in soil and crop management [73]. In that study, drought was associated with an average yield loss of about 13%, while high-intensity precipitation combined with sustained wetness produced an average loss of about 36% [73]. Drainage, soil properties, irrigation, and management altered the response to the same broad event. These results cannot be transferred directly to other crops or Mediterranean conditions. They do, however, illustrate a broader point: identifying an extreme at regional scale is insufficient to predict its agricultural consequences. Field heterogeneity is part of the impact process, not simply uncertainty around an average response.

7.3. Parcel-Scale Drought and Flood Proneness in North-Western Crete

The north-western Crete study linked 1960–2019 station records with the spatial distribution of tree-crop parcels [15]. SPI showed a slight downward tendency across stations, with varying statistical support. The limited station-level significance does not establish the absence of a trend, while the common direction alone is insufficient for detection or anthropogenic attribution. The inference therefore remains confined to the observed record and method. Dry and wet extreme episodes also occurred more frequently during the most recent three decades [15]. This behaviour is not fully captured by a monotonic SPI trend. For perennial tree crops, the sequencing of extremes may be particularly important. Prolonged water deficit can increase irrigation demand and plant stress, while subsequent intense precipitation may generate runoff, erosion, or local flooding rather than effective root-zone replenishment.

Station information was combined with hydrological, topographic, and land-surface characteristics to identify parcels prone to drought, flooding, or both. Approximately 24.67% of the mapped tree-crop parcels were classified as exposed to at least one of these pressures [15]. Terrain position, runoff accumulation, drainage, and other site characteristics produced a spatially uneven pattern within the same broader climatic setting. These classes represent proneness or exposure, not complete risk, which also requires crop sensitivity, irrigation reliability, economic value, management capacity, and other dimensions of vulnerability [16,57]. No direct attribution of parcel patterns to

anthropogenic climate change was attempted; the value lies in identifying priorities for monitoring and adaptation.

7.4. Lessons Across Scales

The three studies address different questions at different scales: global drought exposure, field-level yield response, and parcel-level proneness. The global analysis shows how results vary with indicator and scenario; the Dutch study estimates realised yield effects within a production system; and the Crete example links station-based hydroclimatic evidence with local landscape controls on exposure. Regional indicators can identify emerging pressure, but field- and parcel-level decisions also require information on soils, topography, drainage, crop characteristics, infrastructure, water access, and management. Section 8 builds on these differences to link hydroclimatic evidence more directly with adaptation choices [15,72,73].

8. Translating Evidence into Water-Resources Adaptation

Water-resources decisions are rarely made after climatic change has been fully detected, attributed, and translated into precise local impacts. More often, planners must act while precipitation projections diverge, hydrological models produce different outcomes, and future demand, infrastructure, land use, and governance remain uncertain [16,17,74–77].

Planning should proceed without waiting for complete certainty, while avoiding commitments that exceed the strength or spatial relevance of the available evidence [16,17,19,78]. The framework developed here brings the decision into focus through three linked questions: How strong is the evidence, and at what spatial scale is it relevant? How vulnerable is the system, and what would be the consequences of delayed action or failure? How costly, long-lived, and reversible is the proposed intervention? These questions do not prescribe a single response. They help determine the degree of commitment that can reasonably be supported by the available evidence.

8.1. Acting Before Attribution Is Complete

Attribution helps separate climatic influences from abstraction, land-use change, reservoir regulation, and other pressures [7,28,52,53]. It improves diagnosis, but complete attribution is not a prerequisite for reducing existing risk. A water system may already perform poorly during drought, intense precipitation, or periods of high seasonal demand even when the underlying climatic trend remains uncertain. Measures addressing current weaknesses can benefit present and future conditions. In agricultural water management, these include leakage control, efficient scheduling, soil-moisture and groundwater monitoring, demand management, alternative sources, and climate-adaptive agronomy [16–18].

Scientific and management conclusions should still be kept separate. An observed streamflow decline may not be attributable specifically to anthropogenic forcing, yet repeated supply failures may justify demand reduction, revised reservoir operation, or source diversification. Attribution concerns the causes of change; adaptation concerns the consequences for system performance. The evidential bar should be higher for interventions that are expensive, long-lived, environmentally consequential, or difficult to reverse. Relevant questions include how close the system is to a critical threshold, what would happen if action were delayed, whether the measure can be expanded or withdrawn, and how costs and benefits are distributed. A *p*-value alone provides little guidance on these issues.

8.2. Starting from System Vulnerability

Top-down assessments commonly begin with emission scenarios and climate projections, which are downscaled and used to drive hydrological or impact models. This remains useful, but uncertainty can accumulate before the analysis reaches the operational question [74,75]. Decision scaling begins with the water system itself. Objectives and failure thresholds are identified first, such as minimum supply reliability, acceptable irrigation deficit, environmental-flow requirements, groundwater drawdown limits, reservoir-storage thresholds, or flood-protection standards. The system is then tested across combinations of climatic and non-climatic stresses to determine where performance becomes unacceptable. Climate projections are used afterwards to assess whether those conditions are plausible or becoming more likely [75].

Decision scaling helps identify which uncertainties would actually alter the choice among options. Large differences among precipitation projections may be of little practical importance if the system performs adequately across all of them. A relatively small change may be critical when storage, groundwater, or irrigation supply is already close to failure. Under deep uncertainty, strategies that perform acceptably across several plausible futures are often preferable to a solution optimised for one expected outcome [17,76,77]. In water management, robustness may favour portfolios combining demand reduction, operational flexibility, distributed storage, groundwater protection, reuse, ecosystem-based measures, and staged infrastructure. A soil–water–crops–energy perspective extends this logic by making explicit the interactions among irrigation demand, soil management, energy use, groundwater pressure, and institutional capacity [79]. No strategy is robust with respect to every objective. Reliability, affordability, agricultural production, environmental flows, and aquifer protection may favour different options. These trade-offs should be reported explicitly rather than absorbed into a single performance score [16,80].

8.3. Adaptive Pathways and Monitoring

Many adaptation choices are better treated as a sequence than as a single permanent decision. Adaptive pathways begin with measures suited to current conditions while retaining further options if system performance deteriorates [19,81].

An adaptation tipping point is reached when an existing strategy can no longer meet its objectives [81]. It may be defined by reservoir reliability, frequency of supply restrictions, groundwater levels, irrigation deficits, flood exceedance, water-quality limits, or ecological thresholds.

Monitoring adds value when it is tied to explicit review points and operational triggers. A pathway should specify:

- Which variables will be monitored;
- What thresholds or rates of change will trigger reassessment;
- How much lead time is required for the next measure;
- Which options must remain technically, financially, and institutionally available.

An initial pathway might include leakage control, demand management, improved operations, managed aquifer recharge, or small-scale storage. Larger infrastructure could remain conditional on evidence that the first measures are becoming insufficient. This sequencing reduces the risks of both premature investment and delayed action.

8.4. Local Targeting and Maladaptation

Higher-resolution information is useful when it represents the local processes that govern the decision. A detailed climate projection may add little if the analysis omits soils, drainage, groundwater access, crop sensitivity, operating rules, or institutional capacity.

In agricultural areas exposed mainly to drought, appropriate measures may include irrigation scheduling, soil–water conservation, recharge protection, crop adjustment, or allocation reform. Where runoff and flooding dominate, drainage maintenance, natural retention, erosion control, protection of flow pathways, and land-use planning may be more relevant. Locations exposed to both drought and excess water require integrated assessment because measures designed for one pressure can worsen the other.

Stakeholder knowledge can identify undocumented withdrawals, feasible thresholds, maintenance constraints, flood pathways, and conflicting objectives [80,82]. In the Cauvery Basin, engagement was combined with socioeconomic scenarios and water-resources modelling to test robustness [83]. Crete provides an operational example in which regional irrigation bulletins, parcel-scale tools, and sensor-based scheduling form a tiered advisory scheme [84]. Such evidence is developed iteratively with decision-makers [16,82,83]. Maladaptation may arise when short-term benefits create longer-term pressure: groundwater pumping can accelerate depletion, flood defences encourage exposure, drainage transfers peaks downstream, and new supply infrastructure can redistribute affordability or access. Measures become maladaptive when they increase long-term vulnerability, shift risk between locations or social groups, damage ecosystems, increase resource dependence, or restrict future options [16,85]. Assessment should extend beyond immediate technical performance to the full water balance, energy use, environmental effects, affordability, equity, and institutional feasibility.

8.5. Linking Evidence to the Level of Commitment

Table 2 provides the practical summary of the proposed framework. It links different forms and levels of hydroclimatic evidence with their interpretation and with a proportionate degree of adaptation commitment. The responses are indicative rather than prescriptive, because vulnerability, coping capacity, costs, and the consequences of failure remain specific to each water system.

Table 2. Linking hydroclimatic evidence to proportionate water-resources adaptation responses. Source: Author’s synthesis based on decision-scaling, robust-decision, and adaptive-pathway approaches [16,17,19,74–78,81].

Hydroclimatic Evidence	Interpretation	Proportionate Response
High present-day variability without a statistically supported long-term trend	Recurrent stress is evident, but persistent directional change has not been established	Monitoring, maintenance, preparedness, efficiency, and other low-regret measures
Common trend direction with limited station-level significance	A regional signal may be emerging, but statistical power or field significance remains limited	Regional assessment, threshold stress testing, targeted vulnerability reduction, and preservation of options
Statistically supported local change without attribution	The observed variable has changed, but climatic and non-climatic contributions remain unresolved	Respond to the observed system change while investigating abstraction, land use, infrastructure, and climatic drivers
Attributed regional change with uncertain local magnitude	The broader causal signal is credible, but its local expression remains conditional	Multiple scenarios, robust portfolios, local vulnerability analysis, and adaptive pathways
High-confidence local impact supported by converging evidence	The risk is sufficiently constrained for targeted intervention	Structural, operational, institutional, or ecosystem-based measures with monitoring and review
Low-probability outcome with severe consequences	Likelihood remains uncertain, but failure would be unacceptable	Safety margins, contingency planning, emergency options, and staged preparatory investment

Stronger climatic evidence does not automatically justify a larger intervention. A highly vulnerable system may need early action even when trend evidence is limited, whereas a statistically robust change may require little additional investment where coping capacity is already adequate. What changes across the evidence levels is primarily the degree of irreversible commitment that can be justified.

Uncertainty should therefore influence the design, timing, and flexibility of adaptation. Limited evidence favours monitoring, learning, low-regret measures, and preservation of future options; stronger and more locally relevant evidence can support targeted and longer-lived interventions. Decisions should still be reviewed as climatic, hydrological, and socioeconomic conditions evolve.

9. Research Gaps and Future Directions

Hydroclimatic research now includes extensive trend analyses, projections, attribution studies, and local impact assessments, but the links among them remain weak. Station records may be analysed without regional forcing or water-use information, attribution studies may offer little basin guidance, and high-resolution climate data may remain operationally irrelevant when disconnected from system thresholds. Future work needs to connect observations and causal inference more directly with local processes and real decisions.

9.1. Long-Term Observations of Climate and Water Management

Many uncertainties begin with the observational record. Short series, missing data, station relocation, changes in instrumentation, altered surroundings, and incomplete metadata can affect estimated trends and their statistical support. These limitations are particularly important for precipitation extremes, streamflow, soil moisture, groundwater, evapotranspiration, and abstraction, for which long and spatially consistent records remain less common than for temperature.

Protecting existing monitoring networks is at least as important as introducing new technologies. Long-term hydrological observatories provide the continuity needed to distinguish gradual change from multidecadal variability, abrupt shifts, and human intervention. A useful monitoring strategy would combine distributed core networks with intensively observed catchments and aquifers where processes can be examined in greater detail [86,87].

Mediterranean networks should better represent coastal, mountainous, island, humid, and semiarid settings. Climatic observations also need to be linked more consistently with records of pumping, irrigation, reservoir operation, interbasin transfers, drainage, and land-use change. Without such information, climatic and management effects remain difficult to separate. Accessible metadata, common quality-control procedures, and interoperable datasets would substantially improve comparisons among regions and spatial scales.

9.2. Stronger Statistical and Causal Analysis

Future trend studies should report effect size and slope uncertainty alongside significance, statistical power, homogeneity, temporal dependence, window sensitivity, and spatial dependence [5,31]. They should also examine changes poorly described by a monotonic trend, including seasonality, variance, persistence, clustering, threshold exceedance, and wet–dry alternation, which may matter more to water management than the annual mean.

Causal analysis should represent climatic and human influences within the same framework. Streamflow and groundwater change cannot be interpreted confidently where abstraction, regulation, irrigation, or land-use change is poorly documented.

Attribution studies would benefit from explicit counterfactuals comparing climatic and management conditions, rather than assigning unexplained residual change to climate by default [52,53].

9.3. Compound Hazards and Process-Relevant Model Evaluation

Drought, heat, flooding, erosion, soil-moisture deficit, and water-quality deterioration are commonly assessed separately, although their effects often arise through combinations or sequences. A prolonged dry period may reduce groundwater levels, increase irrigation demand, and weaken vegetation before intense precipitation produces erosion or flash flooding. The resulting runoff depends on antecedent soil moisture, storage, land cover, and previous disturbance.

Compound-event frameworks can represent multivariate, preconditioned, temporally compounding, and spatially connected hazards [88]. Research should examine whether climatic extremes are becoming more closely clustered, alternating more rapidly, or amplifying the effects of preceding events. This is especially relevant in Mediterranean agricultural systems, where heat, drought, intense precipitation, erosion, and waterlogging may occur within the same growing season.

Models should also be evaluated against the variables and processes relevant to their intended use. Reproducing mean streamflow is not sufficient if drought duration, flood timing, recharge, soil moisture, or interannual storage dynamics are poorly represented. Irrigation analysis requires credible seasonal evapotranspiration and root-zone water balances; groundwater planning depends on recharge timing and long-term storage; flood assessment requires adequate representation of antecedent conditions and event-generating mechanisms.

Large-scale models increasingly include reservoirs, irrigation, withdrawals, and sectoral demand, but human–water interactions are often represented too schematically to reproduce operating decisions realistically [89]. Agreement among models should not be treated automatically as evidence of accuracy, particularly when they share structural assumptions or forcing datasets [90]. Observational, internal-variability, climate-model, downscaling, hydrological-model, scenario, and management uncertainties should be distinguished where the available information permits [3,71].

9.4. Decision-Relevant and Co-Produced Evidence

More detailed climate information is not necessarily more useful. Water managers may need estimates of reservoir failure, irrigation-deficit duration, groundwater-threshold exceedance, or the time remaining before an adaptation measure becomes ineffective. These metrics can be more relevant than a detailed seasonal precipitation projection. Identifying them requires sustained interaction among researchers, water managers, farmers, infrastructure operators, and affected communities. Evidence from climate-service co-production indicates that useful indicators are often refined through repeated interaction rather than obtained in a single consultation. This process clarifies scientific capabilities, operational constraints, objectives, and acceptable levels of risk [82,83].

Co-production should influence the research questions, selected variables, performance thresholds, treatment of uncertainty, and comparison of adaptation options. This co-production agenda can be broadened through One Water approaches, which link reuse, digital monitoring, and coordinated governance across agricultural, urban, and environmental water uses [91]. Local participation can also reveal undocumented pumping, informal allocation practices, maintenance constraints, flood pathways, and institutional limitations that are absent from formal datasets but important for system behaviour. The key practical question is which uncertainties could change the preferred

decision. Progress requires stronger links between observations, causal analysis, impact assessment, and adaptation decisions, rather than more stand-alone indicators.

10. Conclusions

Hydroclimatic evidence cannot be carried unchanged from one variable, period, scale, or management setting to another. Climatic forcing is progressively filtered through hydrological processes, landscape characteristics, infrastructure, water use, and the observational record. Variability, trend, statistical significance, detection, and attribution therefore need to remain distinct: trends describe observed records; statistical significance concerns a model-based null hypothesis; detection compares change with expected internal variability; and attribution compares causes. Keeping these distinctions explicit avoids both overstatement of causation and dismissal of changes that matter operationally.

A broad pattern nevertheless emerges: Large-scale signals are usually better constrained, while local responses depend more heavily on hydrological and management conditions. Confidence is highest for warming and rising atmospheric evaporative demand and is also substantial for heavy precipitation and several large-scale hydrological responses. Local precipitation, flooding, recharge, groundwater, and managed supply remain less uniform because broad forcing is mediated by circulation, storage, catchment and aquifer properties, infrastructure, abstraction, and demand. Large-scale attribution is informative but cannot be transferred mechanically to individual basins or sites. Local observations and process-based studies remain essential for identifying where broad pressures intersect with exposure, vulnerability, and system performance.

The scale-aware decision framework developed in Section 8 and summarised in Table 2 brings together three elements that are often considered separately: the strength and local relevance of the hydroclimatic evidence, the vulnerability of the water system and the consequences of failure, and the lifetime and reversibility of the proposed response. Its purpose is not to prescribe a single intervention, but to help determine what degree of adaptation commitment can reasonably be supported by the available evidence. Low-regret, reversible, and adjustable measures can address present vulnerabilities even where local attribution remains incomplete. Expensive, long-lived, or difficult-to-reverse interventions require stronger locally relevant evidence, stress testing across plausible futures, explicit consideration of trade-offs, and preservation of alternatives. The evidential requirement should therefore generally rise with the cost, lifetime, and irreversibility of the intervention, while high present-day vulnerability may still justify early low-regret action.

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