Climate-Related Water Unavailability Risk in the Poro Region, Côte d'Ivoire: Impact Chain and Indicators.

Abstract: Background: Climate-related water shortages depend on hydroclimatic pressure and on the exposure and vulnerability of water-dependent systems. This study develops a factor-based framework for assessing climate-related water unavailability in the Poro Region of northern Côte d'Ivoire, while distinguishing causal factors from indicators.

Methods: A narrative review of scientific and institutional literature was combined with a three-day multidisciplinary expert workshop involving hydrology, pedology and sociology. Experts defined the risk, organized causal factors into hazard, exposure, sensitivity and adaptive capacity, and selected indicators after consensus on the causal structure.

Results: The impact chain contains factors and causal links only, while a separate measurement framework contains 36 indicators: 7 for hazard, 7 for exposure, 9 for sensitivity and 13 for adaptive capacity. Hazard links warming, disrupted rainy-season timing, prolonged dry spells, evapotranspiration, drought, water deficit and reduced recharge to declining surface-water and groundwater availability. Exposure covers populations, social infrastructure, agro-pastoral activities and water-dependent systems. Sensitivity addresses storage limitations, water dependence, seasonal scarcity, vegetation loss and soil sealing, while adaptive capacity addresses governance, monitoring, crisis preparedness, infrastructure maintenance and local planning.

Conclusion: Separating components, factors and indicators preserves causal logic, limits conceptual double counting and provides a transparent basis for future quantitative assessment in the Poro Region and comparable Sudanian territories.

Keywords: climate risk; water unavailability; impact chain; adaptive capacity; Poro Region

1. INTRODUCTION

Water availability is controlled by the timing, amount and spatial distribution of precipitation, by atmospheric water demand, and by the capacity of catchments, soils and aquifers to store and release water. Climate change can alter all these processes simultaneously. Rising temperatures increase evaporative demand, rainfall can become more variable, and longer rainless sequences can intensify both meteorological and hydrological drought. The resulting pressure is especially important in regions where domestic supply, rain-fed agriculture, livestock production and local ecosystems depend on a short rainy season and on limited storage in reservoirs and weathered basement aquifers [1,20].

A water shortage does not become a societal risk solely because rainfall decreases. Consequences depend on the number and location of people and activities requiring water, the sensitivity of water-dependent systems, and the ability of institutions and infrastructure to anticipate, absorb and respond to the disturbance. The Fifth Assessment Report of the Intergovernmental Panel on Climate Change therefore conceptualizes climate risk as arising from the interaction of hazard, exposure and vulnerability [1]. This framing remains central to contemporary climate-risk assessment and adaptation planning [7,20].

Impact chains translate this general concept into a context-specific causal model. The chain itself is constructed from factors and the causal relationships linking them to the defined risk. Indicators are selected only afterwards to measure or approximate those factors. This distinction is essential: a factor expresses why risk is produced, whereas an indicator is an observable or calculable variable used to quantify that factor. Maintaining the separation between the conceptual chain and its measurement system improves transparency, limits confusion between causes and data, and prevents the availability of a convenient dataset from determining the causal structure of the assessment [2–6].

Northern Côte d'Ivoire is characterized by strong rainfall seasonality and a prolonged dry period. In the Poro Region, water use is closely linked to domestic needs, rain-fed and irrigated agriculture, livestock, boreholes, small reservoirs and hydro-agricultural dams. Previous rainfall characterization has shown substantial spatial and temporal variability within the region [15]. At the national level, agriculture, livestock, land use and water resources are among the sectors identified as vulnerable to climate change, while adaptation planning continues to emphasize improved climate information, sectoral integration and local implementation [16,17].

Most climate analyses in the area assess rainfall variability, drought indices or isolated hydrological processes. These analyses are essential, but they do not by themselves identify why similar hydroclimatic conditions can generate different levels of impact between localities. A specific framework is therefore required to connect climatic drivers to surface-water and groundwater availability, to represent the populations and productive activities that depend on these resources, and to incorporate the biophysical and institutional conditions that determine vulnerability.

The objective of this study was to develop a factor-based impact chain and a separate indicator framework for the climate-related risk of water unavailability in the Poro Region. More specifically, the study aimed to: (i) identify the causal factors linking climate signals to reduced surface-water and groundwater availability; (ii) organize exposure, sensitivity and adaptive-capacity factors in accordance with the IPCC AR5 risk framework; (iii) select indicators capable of describing the retained factors at local scale; and (iv) clarify conceptual overlaps among related indicators. The study is limited to construction of the chain and definition of the indicator framework. It does not select specific databases, harmonize spatial resolutions, assign ordinal scores, normalize or weight variables, or calculate a composite index or risk map.

2. MATERIALS AND METHODS

2.1. STUDY CONTEXT AND RISK DEFINITION

The Poro Region is located in northern Côte d'Ivoire and belongs to the Sudanian climatic domain. Rainfall is concentrated in one main wet season, followed by a marked dry season. The regional economy and rural livelihoods depend strongly on agriculture and livestock, while towns, villages, schools, health facilities and productive activities rely on a combination of groundwater abstraction, local surface waters, reservoirs and dams. This seasonal dependence makes the territory sensitive not only to annual rainfall totals but also to rainfall timing, dry-spell duration, evaporative demand and the capacity of water bodies and aquifers to maintain supplies during the dry season [15–17].

The risk considered in this study was defined as the possibility that available surface water and groundwater become insufficient, in time or space, to meet the needs of populations, agricultural and pastoral activities, local water systems and water-dependent ecosystems. This definition focuses on resource availability rather than on the occurrence of a single climatic event. It therefore includes meteorological drought, hydrological drought, reduced river flow, reservoir drying, reduced groundwater recharge and declining groundwater levels as connected processes.

2.2. CONCEPTUAL FRAMEWORK

The study followed the IPCC AR5 climate-risk framework, in which risk results from interactions among hazard, exposure and vulnerability [1]. For operational presentation, vulnerability was divided into sensitivity and adaptive capacity, yielding four analytical blocks: hazard, exposure, sensitivity and adaptive capacity. In this study, a component is one of these broad analytical blocks. A factor is a causal, biophysical, social, institutional or organizational element placed within a component and represented in the impact chain. An indicator is a measurable variable selected after the chain has been constructed to quantify one factor or one clearly defined aspect of that factor. Indicators were therefore not treated as nodes of the conceptual chain.

$$R = f(H, E, V) \quad (1)$$

where R is climate-related risk, H is hazard, E is exposure and V is vulnerability. Within the operational framework, vulnerability reflects both sensitivity and adaptive capacity. Sensitivity factors increase the severity of water-shortage impacts, whereas adaptive-capacity factors describe the ability to prevent, monitor, anticipate, maintain services and respond. Adaptive-capacity indicators were formulated positively where possible; when incorporated into a vulnerability index, their direction should be transformed so that higher final vulnerability consistently represents higher risk.

2.3. LITERATURE AND DOCUMENTARY REVIEW

A narrative review was conducted to identify established concepts, causal relationships and measurable indicators relevant to climate-related water availability. The reviewed material covered the IPCC risk framework, impact-chain methods, drought and climate-extreme indices, evapotranspiration and crop-water requirements, hydrological monitoring, groundwater in weathered crystalline rocks, domestic water needs, integrated water-resources management and national adaptation planning [1–19]. Scientific publications were complemented by institutional reports because several adaptive-capacity factors—such as governance, monitoring coverage, maintenance and local planning—are documented primarily through administrative and policy sources. The review was not designed as a systematic meta-analysis; its purpose was to provide an evidence base for a context-specific conceptual model.

2.4. MULTIDISCIPLINARY EXPERT WORKSHOP

The framework was developed during a three-day multidisciplinary workshop involving a panel of experts in hydrology, pedology and sociology. The workshop was organized in two successive stages. The first stage was conceptual. Participants agreed on the risk to be assessed, distinguished water unavailability from flooding and water-quality deterioration, identified the factors belonging to each component, and discussed the causal links connecting those factors to the final risk. At the end of this stage, the impact chain contained factors only. The second stage was operational. Candidate indicators were then proposed for measuring the retained factors, compared with the literature, reformulated where necessary and assigned to the appropriate component. The process sought expert consensus rather than a numerical expert score.

2.5. CONSTRUCTION OF THE IMPACT CHAIN AND SELECTION OF INDICATORS

The construction of the impact chain preceded the selection of indicators. During chain construction, factors were retained according to their causal relevance to the defined risk and their coherence with the Poro context. Data availability did not determine the factor structure. After the chain had been agreed, indicators were assessed using five considerations: direct relevance to the corresponding factor; interpretability at regional or subregional scale; limited redundancy with other indicators; methodological clarity; and practical measurability in the Poro context. This last consideration ensured that each indicator could be clearly defined and documented, without prescribing a particular database or calculation method.

Each retained indicator was mapped to a named factor, but the indicators were listed in separate operational tables and were not inserted into the impact-chain figure. Terminological overlaps were harmonized. Consecutive dry days and the CDD index were treated as one indicator. Density of modern water points was assigned to exposure because it represents hydraulic assets and users dependent on groundwater abstraction, whereas borehole functionality and maintenance frequency were assigned to adaptive capacity. Similarly, livestock density represents the magnitude of exposed animals, while livestock water requirement represents their sensitivity to shortage. The final measurement framework contains 36 indicators: 7 for hazard, 7 for exposure, 9 for sensitivity and 13 for adaptive capacity. Not every intermediate-impact node in the chain was assigned a distinct indicator. Some intermediate impacts were retained to preserve the causal continuity between climatic drivers and the final reduction in water availability, while the selected indicators operationalize the principal measurable hazard factors.

2.6. ORGANIZATION AND INTERPRETATION OF THE RETAINED INDICATORS

Seven indicators were retained to describe the hydroclimatic hazard factors: SPEI-12, Consecutive Dry Days (CDD), delay in the onset of the rainy season, temperature anomaly, potential evapotranspiration estimated with the FAO-56 Penman–Monteith method, estimated groundwater recharge, and the climatic water balance expressed as precipitation minus potential evapotranspiration (P − ETP). CDD, delayed rainy-season onset, temperature anomaly and potential evapotranspiration have a direct relationship with hazard. SPEI-12, groundwater recharge and P − ETP have an inverse relationship because lower values indicate more severe water deficit or weaker resource replenishment. This directional distinction was recorded to clarify the meaning of each indicator; no standardization, transformation or aggregation was performed in this study.

The same interpretive logic was applied to the other components. Higher exposure and sensitivity indicate stronger potential consequences, whereas stronger adaptive capacity reduces vulnerability. For qualitative indicators related to governance, planning and institutional capacity, the observable content to be assessed was defined, but no ordinal scores were assigned. The study did not undertake data collection, spatial harmonization, normalization, weighting or aggregation.

3. RESULTS

3.1. FACTOR-BASED STRUCTURE OF THE IMPACT CHAIN

Figure 1 presents the conceptual impact chain. It contains factors and causal relationships only; the indicator names are intentionally excluded. The hazard pathway begins with rising temperatures, disrupted rainy-season timing and prolonged dry spells. These drivers contribute to increased potential evapotranspiration, climatic drought, climatic water deficit and reduced groundwater recharge. Their combined effect is a decline in the temporal and spatial availability of surface water and groundwater. This pathway does not assume that annual precipitation must decrease monotonically. Water availability can deteriorate through changes in rainfall timing, longer rainless periods, warming and increasing evaporative demand even where annual rainfall trends remain weak or spatially contrasted.

The decline in water availability becomes a risk through its interaction with the other components. Exposure is represented by human and social presence, agro-pastoral activities, and water systems and hydraulic infrastructure. Sensitivity is represented by four risk-increasing factors: limited natural water-retention and storage capacity, high dependence of water uses, high dependence on seasonal water availability, and vegetation-cover degradation and soil sealing. Limited adaptive capacity is represented by a low level of integrated water governance, insufficient hydroclimatic and hydrogeological monitoring, limited capacity to anticipate water crises, low functionality and insufficient maintenance of hydraulic infrastructure, and limited integration of climate change into local planning. These factor groups converge toward the final risk of water unavailability in the Poro Region.

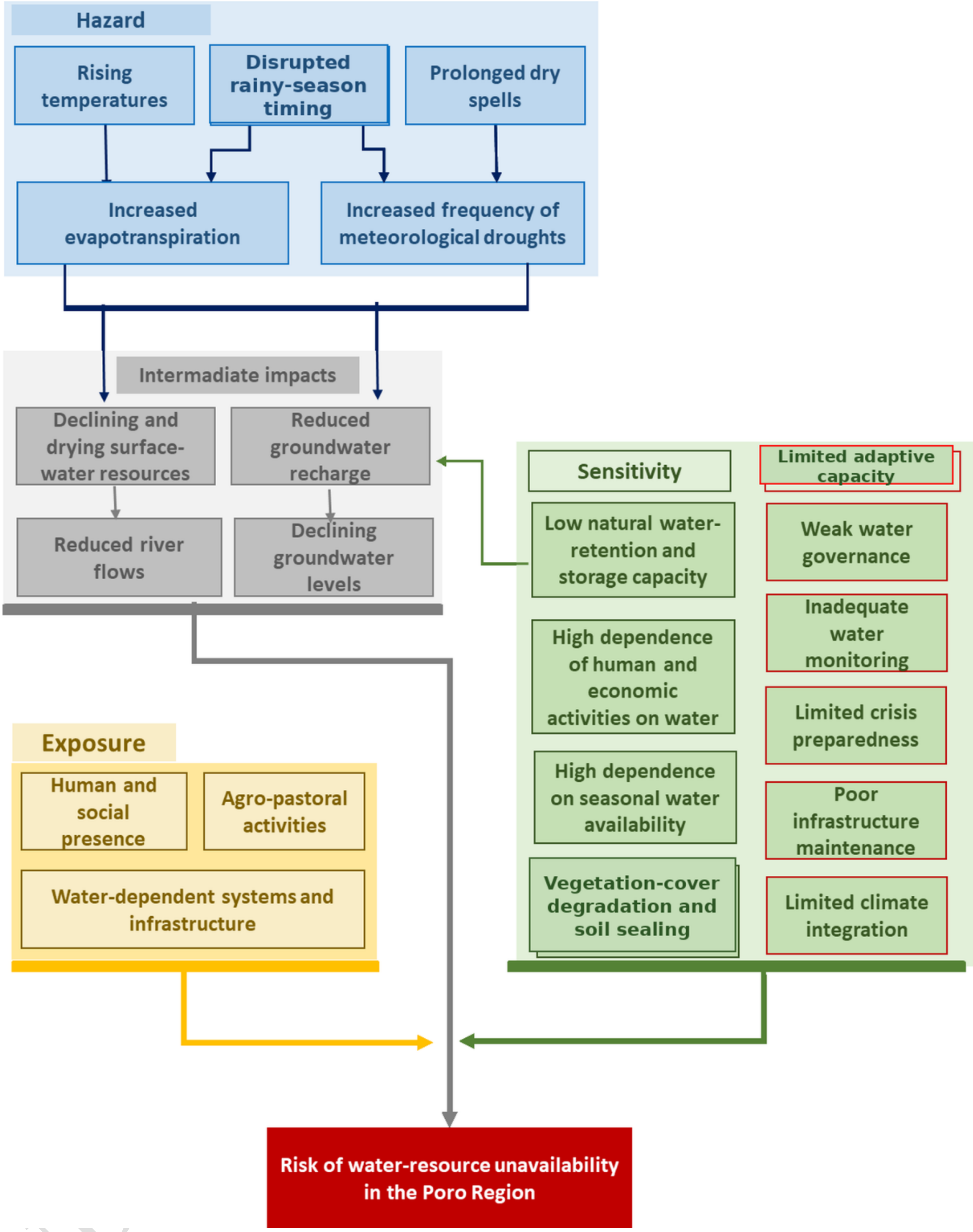

Figure 1. Factor-based impact chain for the climate-related risk of water unavailability in the Poro Region. The figure contains factors only; the corresponding indicators are presented separately in Tables 2–5. Source: Authors' construction based on the IPCC AR5 framework, literature review and multidisciplinary workshop.

3.2. FROM CONCEPTUAL FACTORS TO MEASURABLE INDICATORS

The impact chain and the indicator framework are two linked but distinct results. The chain identifies the causal and contextual factors that produce risk. The indicator framework translates those factors into observable or calculable variables without inserting the indicators into the conceptual chain. A single factor can require more than one indicator, while some intermediate effects may be interpreted through several complementary indicators. Thirty-six indicators were retained: 7 for hazard, 7 for exposure, 9 for sensitivity and 13 for adaptive capacity. Table 1 summarizes the factors shown in the chain and the number of indicators retained separately for each component.

Table 1. Components and factor groups of the impact chain, with the number of indicators retained separately for operationalization.

Operational component	Factor groups represented in the impact chain	Retained indicators (n)	Analytical role
Hazard	Rising temperatures; disrupted rainy-season timing; prolonged dry spells; increased potential evapotranspiration; climatic drought; climatic water deficit; reduced groundwater recharge; declining and drying surface-water resources; reduced river flows; declining groundwater levels; reduced temporal and spatial availability of surface water and groundwater	7	Represent the climatic and hydrological processes that reduce the amount, renewal and seasonal persistence of available water.
Exposure	Human and social presence; agro-pastoral activities; water systems and hydraulic infrastructure	7	Represent people, livelihoods, essential services and hydraulic assets located in the affected territory.
Sensitivity	Limited natural water-retention and storage capacity; high dependence of water uses; high dependence on seasonal water availability; vegetation-cover degradation and soil sealing	9	Represent the conditions that make exposed systems more strongly affected by reduced water availability.
Limited adaptive capacity	Low level of integrated water governance; insufficient hydroclimatic and hydrogeological monitoring; limited capacity to anticipate water crises; low functionality and insufficient maintenance of hydraulic infrastructure; limited integration of climate change into local planning	13	Represent the institutional, technical and organizational capacities that can reduce vulnerability.
Total	Four operational components; factor groups are shown in the chain, while indicators remain in separate measurement tables	36	Provide the conceptual and operational architecture for a subsequent spatial risk assessment.

3.3. HAZARD FACTORS AND CORRESPONDING INDICATORS

The hazard factors were defined in the conceptual chain before the variables used to measure them were chosen. Seven indicators were subsequently retained. SPEI-12 measures climatic drought resulting from the combined influence of precipitation and atmospheric water demand. CDD measures the persistence of rainless conditions, while delayed onset represents disruption of the seasonal calendar. Temperature anomaly captures warming, and FAO-56 Penman–Monteith potential evapotranspiration represents atmospheric demand. Estimated groundwater recharge measures renewal of subsurface reserves, whereas P − ETP represents the climatic balance between water inputs and potential atmospheric losses. These indicators operationalize the hazard factors without becoming factors themselves.

Table 2. Hazard factors and corresponding indicators retained for the assessment of water unavailability.

Hazard factor	Retained indicator	Relationship to hazard	Definition and interpretation
Climatic drought	SPEI-12	Inverse	Dimensionless 12-month drought index; lower and more negative values indicate stronger combined precipitation and evaporative deficit [11].
Prolonged dry spells	Consecutive Dry Days (CDD)	Direct	Annual maximum number of consecutive days with precipitation below 1 mm; higher values indicate longer rainless periods [9].
Disrupted rainy-season timing	Delay in the onset of the rainy season	Direct	Number of days of delay relative to the adopted onset reference; a later onset shortens the effective wet and growing season.
Rising temperatures	Temperature anomaly	Direct	Degrees Celsius relative to the reference-period mean; positive values indicate warming and stronger thermal pressure on water resources.
Increasing atmospheric water demand	Potential evapotranspiration (FAO-56 Penman–Monteith)	Direct	Millimetres over the selected period; higher values indicate stronger atmospheric demand for water [12].
Decline of groundwater replenishment	Estimated groundwater recharge	Inverse	Millimetres or volume per year; lower values indicate weaker renewal of groundwater reserves.

Hazard factor	Retained indicator	Relationship to hazard	Definition and interpretation
Climatic water deficit	Climatic water balance (P − ETP)	Inverse	Millimetres over the selected period; lower or negative values indicate that potential atmospheric losses approach or exceed precipitation inputs.

3.4. EXPOSURE FACTORS AND CORRESPONDING INDICATORS

The exposure component contains three factor groups: human and social presence, agro-pastoral activities, and water systems and hydraulic infrastructure. These factors describe what is present in the territory and can be affected by reduced water availability. Seven indicators were retained to quantify the population and essential services exposed, the extent of water-dependent agricultural and pastoral livelihoods, and the hydraulic assets or surface-water systems on which localities depend. Exposure indicators therefore measure the presence or concentration of elements at risk; they do not measure their intrinsic fragility or their capacity to respond.

Table 3. Exposure factors and corresponding indicators retained for the assessment of water unavailability.

Exposure factor	Retained indicator	Definition and interpretation
Human and social presence	Population density	Inhabitants per square kilometre (inh. km^{-2}); indicates the concentration of people requiring domestic water.
	Density of health and education facilities	Number of health centres and schools per 100 km^2 or per local administrative unit; identifies essential services with high continuity requirements.
Agro-pastoral activities	Area of sensitive crops	Hectares of lowland and market-gardening crops; represents water-dependent production directly exposed to seasonal shortage.
	Number of agricultural and pastoral households	Households per locality or administrative unit; represents the social extent of livelihood exposure.
	Livestock density	Tropical Livestock Units per square kilometre (TLU km^{-2}); represents animals dependent on pastoral water points.
Water systems and hydraulic infrastructure	Density of modern water points	Number of boreholes and human-powered pumps per 100 km^2 or per locality; represents water-supply assets dependent on groundwater.
	Proximity to and dependence on reservoirs and hydro-agricultural dams	Mean distance in kilometres, number of dependent localities or serviced agricultural area; describes dependence on surface-water storage.

3.5. SENSITIVITY FACTORS AND CORRESPONDING INDICATORS

Sensitivity contains four factors formulated in the direction of increased risk. Limited natural water-retention and storage capacity is measured through soil texture and depth, available water capacity and the thickness of the weathered layer. High dependence of water uses is represented by domestic, irrigation and livestock water requirements. High dependence on seasonal water availability is measured by the number of months with low water availability, which represents the recurring duration of annual stress for water-dependent systems. Vegetation-cover degradation and soil sealing are represented by deforestation and the expansion of built-up and impervious surfaces. Together, these nine indicators explain why similar levels of exposure can produce different levels of impact when water availability declines.

Table 4. Sensitivity factors and corresponding indicators retained for the assessment of water unavailability.

Sensitivity factor	Retained indicator	Definition and interpretation
Limited natural water-retention and storage capacity	Soil texture and soil depth	Percentage sand and clay, combined with profile depth; supports interpretation of infiltration and water retention.
	Soil water-holding capacity / available water capacity	Millimetres of plant-available water in the soil profile; low values indicate limited buffering between rainfall events.
	Thickness of the weathered layer (alterites)	Metres; indicates the potential storage volume in weathered basement materials, subject to local hydrogeological conditions [14].

Sensitivity factor	Retained indicator	Definition and interpretation
High dependence of water uses	Domestic water use per person	Litres per person per day (L $person^{-1}$ day^{-1}); represents the unit domestic requirement and should be spatially differentiated when possible [13].
	Agricultural irrigation-water requirement	Cubic metres per hectare or millimetres per crop cycle; water required to compensate crop-water deficit [12].
	Livestock water requirement	Litres per TLU per day or cubic metres per locality; unit requirement of the livestock population.
High dependence on seasonal water availability	Number of months with low water availability	Months per year below a defined availability threshold; represents the duration of recurrent annual stress.
Vegetation-cover degradation and soil sealing	Deforestation rate	Percentage annual or period-specific loss of tree and natural vegetation cover; indicates reduced ecological regulation and possible changes in infiltration and runoff.
	Built-up and impervious-surface expansion rate	Percentage annual or period-specific increase in built-up/impervious area; indicates increasing soil sealing and altered recharge conditions.

3.6. ADAPTIVE-CAPACITY FACTORS AND CORRESPONDING INDICATORS

Limited adaptive capacity is represented by five factors formulated as constraints that increase vulnerability: a low level of integrated water governance, insufficient hydroclimatic and hydrogeological monitoring, limited capacity to anticipate water crises, low functionality and insufficient maintenance of hydraulic infrastructure, and limited integration of climate change into local planning. Thirteen indicators were retained to describe the corresponding institutional, technical and organizational capacities. Most are expressed positively, such as the existence of management structures, monitoring coverage or the proportion of functional boreholes. Their interpretation is therefore inverse to vulnerability: stronger capacity corresponds to lower vulnerability. This directional meaning is stated in the framework, but no score was reversed or combined in this article.

Table 5. Adaptive-capacity factors and corresponding indicators retained for the assessment of water unavailability.

Factor indicating limited adaptive capacity	Retained indicator	Definition and interpretation
Low level of integrated water governance	Existence of local water-management structures	Ordinal indicator based on explicit criteria distinguishing formal existence, recognized mandate, documented activity and effective participation.
	Number of functional water-management committees	Number or proportion of committees meeting predefined functionality criteria, such as regular meetings, documented decisions and follow-up actions.
Insufficient hydroclimatic and hydrogeological monitoring	Density of hydrometric stations	Number of stations per 10,000 km² or per basin; interpreted against monitoring objectives and terrain [8].
	Hydrological-network coverage relative to a target	Percentage of a context-specific target density or proportion of territory adequately monitored; avoids mechanical use of one universal standard.
	Institutional capacity for groundwater monitoring	Ordinal assessment based on observable evidence concerning operational piezometers or observation wells, trained staff, procedures, records and data-management arrangements.
	Density of meteorological stations	Number of operational stations per 10,000 km² or proportion of territory within an appropriate observation radius.

Table 5 (continued).

Factor indicating limited adaptive capacity	Retained indicator	Definition and interpretation
Limited capacity to anticipate water crises	Existence of drought-management plans	Ordinal indicator based on explicit evidence of an adopted plan, warning triggers, assigned responsibilities, response procedures and review mechanisms.
	Number of communal water-management plans	Number or proportion of communes with a plan meeting predefined operational criteria for allocation, shortage management and priority uses.
Low functionality and insufficient maintenance of hydraulic infrastructure	Functional borehole rate	Percentage of inventoried boreholes delivering the expected service at the assessment date.
	Operational hydraulic-works rate	Percentage of water-supply, storage and distribution works meeting defined operating criteria.
	Maintenance frequency	Number of preventive and corrective maintenance actions per year, or ordinal compliance with a predefined maintenance schedule and verification guide.
Limited integration of climate change into local planning	Integration of National Adaptation Plan priorities into local development plans (PCDs)	Ordinal assessment based on explicit criteria for treatment of climate, drought and water availability in local development plans, including actions, responsibilities, budgets and monitoring [16].
	Number of local water-adaptation projects	Number of active or completed projects addressing water storage, efficiency, monitoring, ecosystem protection or drought resilience.

3.7. CONCEPTUAL SEPARATION OF FACTORS AND INDICATORS AND RULES FOR OVERLAP

The separation between factors and indicators also helps resolve variables that can appear to belong to more than one component. Classification was based first on the causal question represented by the factor and then on the specific quantity measured by the indicator. Population density, for example, quantifies human presence under exposure; per-capita water use quantifies the intensity of dependence under sensitivity. Water-point density describes exposed hydraulic assets, whereas borehole functionality and maintenance describe adaptive capacity. Table 6 summarizes the principal distinctions. These rules are essential because interpreting the same underlying quantity as evidence for more than one component can artificially amplify its influence.

Table 6. Rules used to distinguish related indicators and limit double counting.

Related concepts	Exposure indicator	Sensitivity or adaptive-capacity indicator	Classification rule
Population and domestic demand	Population density	Domestic water use per person	Population measures how many people are present; per-capita use measures the unit intensity of dependence. If per-capita use is constant, it should not be used to reproduce total population demand.
Livestock and livestock-water demand	Livestock density	Water requirement per TLU	Density measures exposed animals; unit requirement measures sensitivity to water shortage.
Crops and irrigation requirement	Area of sensitive crops	Irrigation-water requirement per hectare or crop cycle	Area measures the exposed production base; water requirement measures the intensity of dependence.
Water-point density and infrastructure condition	Density of modern water points	Functional borehole rate and maintenance frequency	Density measures exposed assets and reliance on groundwater; functionality and maintenance measure capacity to sustain service.
Seasonal scarcity and drought hazard	—	Number of months with low water availability	This indicator represents the recurring duration of system stress in the present framework; its overlap with SPEI-12, CDD, climatic water balance and recharge should be examined whenever the indicators are interpreted jointly.

4. DISCUSSION

4.1. ADDED VALUE OF A FACTOR-FIRST, WATER-AVAILABILITY-SPECIFIC IMPACT CHAIN

The principal contribution of the framework is that the causal structure was defined before indicator selection. This factor-first sequence prevents the impact chain from becoming a simple inventory of available datasets. It also makes explicit the transition from climate pressure to resource unavailability. Annual rainfall decline is not treated as a necessary condition for hazard. Instead, the chain identifies rainfall timing, prolonged dry spells, warming, evaporative demand, climatic drought, negative water balance and reduced recharge as connected factors. The selected indicators then measure these factors through delayed onset, CDD, temperature anomaly, potential evapotranspiration, SPEI-12, P − ETP and estimated groundwater recharge. This is important in the Poro Region because hydroclimatic stress can increase through warming and evaporative demand even where annual precipitation trends are weak or spatially contrasted. SPI was considered conceptually [10], but SPEI-12 was retained because it incorporates atmospheric water demand and is therefore more responsive to drought intensification under warming conditions [11].

The simultaneous retention of SPEI-12, P − ETP and potential evapotranspiration provides complementary descriptions of three related but non-identical factors: standardized climatic drought, absolute climatic water deficit and atmospheric demand. Because these indicators share climatic inputs, they may also contain overlapping statistical information. The present article identifies this conceptual distinction but does not test multicollinearity, because no dataset is assembled and no aggregation is performed. When the indicators are used together quantitatively, pairwise correlation analysis and principal component analysis can determine whether they contribute sufficiently distinct information. Variance inflation factors may also be considered when the indicators are introduced into a regression or another linear modelling framework. The same caution applies to CDD and delayed onset: the first measures the persistence of dry sequences, whereas the second measures displacement of the beginning of the rainy season.

The combined surface-water and groundwater pathway is also suited to the Poro context. During the dry season, reduced reservoir storage and river flow can increase pressure on boreholes, while weak recharge can reduce the reliability of the groundwater resource on which those boreholes depend. In weathered crystalline-rock aquifers, storage and transmissive properties are strongly influenced by the weathering profile and fissured zone [14]. Including soil water-holding capacity and alterite thickness under sensitivity therefore connects the conceptual factors to the physical characteristics that regulate short-term soil-water buffering and longer-term groundwater storage.

4.2. DISTINGUISHING EXPOSURE, SENSITIVITY AND ADAPTIVE CAPACITY

The framework avoids defining vulnerability only through poverty or generalized social disadvantage. It identifies concrete factors that matter for water availability. Exposure describes what is present: people, schools, health facilities, crops, livestock and hydraulic assets. Sensitivity explains why those exposed elements can be more severely affected: limited natural water-retention and storage capacity, high dependence of domestic and productive uses on water, prolonged dependence on seasonal availability, and the degradation of vegetation cover and sealing of soils. Limited adaptive capacity describes the institutional, monitoring, anticipatory, maintenance and planning constraints that reduce the territory's ability to manage shortages. Indicators are attached to these factors only after their conceptual role has been established. This separation improves interpretation because each component points to a different type of intervention.

The distinction between density of modern water points and functionality of boreholes illustrates this principle. A locality with many boreholes can have high exposure because a large part of its supply system depends on groundwater. The same locality can nevertheless have stronger adaptive capacity if the boreholes are functional and maintained. Combining the two variables without preserving their conceptual roles would obscure this difference. The same reasoning applies to crop area versus irrigation requirement and to livestock density versus livestock water requirement.

Some indicators remain context-dependent. The number of months with low water availability could represent a hazard factor if it is defined strictly from hydrological thresholds. It was retained under sensitivity here because it describes the recurring duration for which water-dependent systems operate under pressure. Its conceptual and statistical overlap with SPEI-12, P − ETP, CDD and estimated recharge should be examined whenever these indicators are interpreted jointly. If it provides no distinct information, it should be combined with a related indicator or treated as an intermediate effect rather than as a separate measure.

4.3. STRENGTHS AND LIMITATIONS OF THE PARTICIPATORY METHOD

The three-day workshop allowed hydrological, soil-related and social perspectives to be integrated into one causal structure. This is consistent with the participatory logic of impact-chain methods, which seek a shared representation of risk and combine local knowledge with quantitative information [2–6]. The two-stage organization was especially useful: experts first debated factors and causal pathways without being constrained by available datasets, and only afterwards examined possible indicators. This reduced the risk that easily accessible climatic or remote-sensing variables would dominate the conceptual model. The approach was particularly valuable for adaptive-capacity factors, because governance, committee functionality, maintenance arrangements and local plans cannot be inferred reliably from climate or satellite data alone.

The approach nevertheless contains limitations. Both factor identification and indicator selection depended partly on expert judgement, and no formal Delphi process or numerical scoring system was applied. The workshop was designed to produce interdisciplinary expert consensus rather than a statistically representative survey. Broader validation involving local administrations, water-service operators, agricultural and livestock representatives, community users and monitoring institutions would strengthen the framework by confirming causal links, identifying missing factors and assessing whether the proposed indicators are understandable and actionable for local decision-makers.

A second limitation concerns unequal measurability. Hydroclimatic factors may be easier to quantify consistently than maintenance quality, governance, committee functionality or the operational content of local plans. The framework addressed this risk by defining factors before indicators and by retaining conceptually important factors even when their measurement requires documentary assessment or expert judgement. This preserves the causal completeness of the chain, but it also means that qualitative indicators require explicit definitions and evidence rules before they are scored.

4.4. MONITORING AND GOVERNANCE IMPLICATIONS

The adaptive-capacity component shows that water-unavailability risk cannot be reduced only by constructing new infrastructure. Monitoring is required to detect changes in rainfall, discharge, reservoir storage and groundwater before service failure occurs. Hydrometric and meteorological station density should be evaluated against the purpose of the network, spatial variability, catchment configuration, terrain and required decision scale rather than against a single universal value [8]. Groundwater monitoring also requires more than the physical presence of piezometers; it depends on observation frequency, data quality control, institutional responsibility, archiving and the use of information in decisions.

The governance indicators are consistent with broader IWRM principles, which emphasize enabling policies, institutional coordination, participation, management instruments and financing [18,19]. Reports on IWRM implementation in Africa have repeatedly identified gaps between formal institutional arrangements and effective implementation, including limited capacity, geographic coverage and financing [18]. For the Poro Region, the proposed indicators therefore distinguish the existence of structures and plans from their functionality. A committee that exists only on paper or a plan without triggers, responsibilities and resources should not receive the same score as an operational mechanism.

Integration of climate change into local development plans is equally important. National adaptation priorities identify agriculture, livestock, land use and water resources among vulnerable sectors in Côte d'Ivoire [16]. The country climate and development assessment also underlines the need to strengthen resilience in northern and poorer regions and to address land degradation [17]. At local level, the chain provides a direct way to translate those priorities into planning questions: Which localities depend most on drying reservoirs? Where are boreholes failing? Which schools and health facilities lack reliable dry-season supply? Which farming areas combine high crop exposure with low soil-water storage? These questions connect indicator assessment to concrete adaptation decisions.

4.5. METHODOLOGICAL SAFEGUARDS FOR USE OF THE INDICATOR FRAMEWORK

The present article stops at construction of the impact chain and definition of the indicators. It neither prescribes a specific dataset nor calculates an index. Three safeguards are nevertheless important whenever the framework is used quantitatively. First, potential redundancy must be examined. SPEI-12, $P - ETP$ and potential evapotranspiration express different aspects of hazard but share climatic inputs. Pairwise correlations and principal component analysis can help determine whether they provide distinct information; variance inflation factors are relevant when the indicators enter a regression or another linear model. Similar checks are appropriate for CDD, rainy-season onset and the number of months with low water availability.

Second, all indicators used in one assessment must refer to a common spatial unit and compatible time period. Gridded climatic or environmental variables can be summarized for the selected administrative or hydrological units, while administrative and infrastructure information should be assigned to the same boundaries. The framework does not impose a single scale: the spatial unit and reference period must follow the purpose of the assessment and be reported explicitly. No spatial or temporal harmonization was performed in the present study.

Third, qualitative indicators related to governance, planning, committee functionality and institutional capacity require standardized scoring guides. Each score should correspond to observable criteria, documentary evidence and predefined decision rules. An ordinal scale such as 1–5 should be adopted only after the meaning of every level has been defined, and independent scoring by more than one evaluator is preferable when feasible. These safeguards concern application of the framework and are not analyses performed in the present study.

5. CONCLUSION

This study developed two complementary outputs for assessing the climate-related risk of water unavailability in the Poro Region of northern Côte d'Ivoire. The first is a conceptual impact chain composed only of factors and causal links. It connects rising temperatures, disrupted rainy-season timing and prolonged dry spells to increased potential evapotranspiration, climatic drought, a negative climatic water balance, reduced groundwater recharge and declining surface-water and groundwater availability. It then links these hazard factors to human and social presence, agro-pastoral activities and hydraulic systems; to limited natural water-retention and storage capacity, high dependence of water uses, high dependence on seasonal water availability, and vegetation-cover degradation and soil sealing; and to limitations in integrated water governance, hydroclimatic and hydrogeological monitoring, crisis anticipation, infrastructure functionality and maintenance, and local climate planning. The second output is a separate measurement framework containing 36 indicators: 7 for hazard, 7 for exposure, 9 for sensitivity and 13 for adaptive capacity. This separation between components, factors and indicators is methodologically important. Components organize the assessment, factors explain how risk is produced, and indicators define the observable variables used to describe those factors. The framework also clarifies common overlaps, including population versus domestic demand, livestock density versus livestock-water requirement, and water-point density versus infrastructure functionality. The article deliberately stops at construction of the chain and definition of the indicators. It does not select specific databases, harmonize spatial resolutions, assign qualitative scores or calculate a composite index. It nevertheless identifies three safeguards for any quantitative use of the framework: statistical examination of related indicators, harmonization to a common spatial and temporal basis, and explicit scoring rules for qualitative institutional indicators. The framework provides a coherent basis for understanding how climatic pressure, water dependence, environmental sensitivity and management capacity combine to shape water-unavailability risk in the Poro Region and may be adapted to other Sudanian territories.

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AUTHOR CONTRIBUTIONS

F.S.: conceptualization, methodology, investigation, visualization, and writing—original draft. K.Y.B.: supervision, validation, and writing—review and editing. Both authors read and approved the final manuscript.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY

No new numerical dataset was generated or analysed in this study. The article reports a factor-based impact chain and a separate indicator framework derived from scientific and institutional literature and a multidisciplinary expert workshop. All conceptual outputs and retained indicators are presented in the article.

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