Water Security as Economic Security

How Scarcity, Floods, Food Systems, Energy, AI Infrastructure and Geopolitics Are Reshaping the Global Economy

A Systems Analysis of Water, Growth, Industry, Finance, Trade and Strategic Resilience to 2040

Academic Research Monograph and Strategic White Paper

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September 2026

Evidence cut-off: 20 September 2026

This monograph treats water security as a core economic-security variable rather than a narrow environmental sector. It integrates hydrology, public health, food systems, energy, manufacturing, artificial-intelligence infrastructure, trade, finance and geopolitics. The study distinguishes scarcity from service failure, withdrawals from consumption, physical risk from governance risk, and current observations from scenarios. It introduces original frameworks for measuring system resilience, asset exposure and early-warning conditions, while retaining explicit limitations and falsifiability tests.

Abstract

Water is simultaneously a human right, an ecological process, a productive input, a transport medium, a public-health service and a strategic asset. These roles are often analysed separately. That separation is increasingly inadequate. Water scarcity can reduce crop yields, constrain thermal and hydroelectric generation, interrupt semiconductor and mining operations, increase urban costs, alter shipping routes, weaken public health and transmit losses into banks, insurers and sovereign balance sheets. Floods and water pollution create a different but equally material set of economic disruptions. The relevant security question is therefore not whether a country or company has access to water in aggregate. It is whether water of the required quantity and quality is available at the required place and time, under institutions capable of allocating it through stress.

The latest hydrological evidence raises the urgency of this question. The World Meteorological Organization reported in September 2026 that 2025 was one of the driest years for global river discharge in 35 years, that the past seven years had the fewest rivers with normal flows since 1991, that terrestrial water storage has declined over the past decade, and that glacier loss occurred across all regions for a fourth consecutive year. (World Meteorological Organization, 2026) These findings sit alongside persistent service deficits. WHO and UNICEF estimate that 2.1 billion people lacked safely managed drinking-water services in 2024, 3.4 billion lacked safely managed sanitation, and 1.7 billion lacked basic hygiene services. (WHO and UNICEF, 2025; World Health Organization, 2026) Water stress is also spatially concentrated. WRI's Aqueduct framework identifies 25 countries containing roughly one quarter of the global population as facing extremely high annual water stress, while at least half of the world's population experiences highly water-stressed conditions for at least one month each year. (Kuzma et al., 2023; World Resources Institute, 2026)

The economic stakes extend beyond water utilities. Agriculture accounts for roughly 69 percent of global freshwater withdrawals in FAO's global aggregate, with large regional variation. (Food and Agriculture Organization of the United Nations, 2026b) Recent FAO material places the share above 70 percent and notes that 1.2 billion people live in agricultural areas facing severe water constraints. (Food and Agriculture Organization of the United Nations, 2026a) OECD work now treats water-related risk as relevant to financial stability because drought, flood, contamination and ecosystem degradation transmit through production, asset values, credit quality, insurance losses and public finances. (OECD, 2025) The OECD's 2026 financing report cites estimates from the Global Commission on the Economics of Water under which long-run water insecurity could reduce global GDP by around 8 percent by 2050, with larger impacts in low-income countries. (Global Commission on the Economics of Water, 2024; OECD, 2026)

Technology does not remove the constraint. Artificial-intelligence infrastructure illustrates the new water-energy-industrial nexus. Data centres consumed roughly 415 TWh of electricity in 2024 and the IEA projects global data-centre electricity demand to exceed 1,000 TWh by 2030

in its base case. (International Energy Agency, 2025b) The local water effect varies sharply with cooling design, climate, electricity supply and siting. Microsoft reports that direct-to-chip cooling designs can save more than 125 million litres of water per facility each year relative to earlier approaches, while semiconductor producers such as Intel and TSMC continue investing in recycling, reclamation and watershed measures because manufacturing remains water dependent. (Intel Corporation, 2026; Microsoft, 2025; Taiwan Semiconductor Manufacturing Company, 2026)

This monograph develops a Water Security Systems Framework with twelve domains: hydrology and source diversity, storage and infrastructure, water quality and treatment, agriculture and food, industry and supply chains, energy and power, cities and WASH, ecosystems and green water, finance and affordability, governance and rights, data and early warning, and transboundary cooperation. It proposes a Water Security Resilience Index based on the geometric mean of domain scores, which prevents strength in one area from fully masking severe weakness in another. It also proposes a Strategic Water Exposure Score for assets and sectors based on dependence, source stress, concentration and recovery difficulty.

The central thesis is that water security is becoming a first-order determinant of economic resilience. The strongest systems will not be those with the largest nominal freshwater endowment. They will be those that combine diversified sources, healthy watersheds, storage, efficient allocation, resilient infrastructure, credible institutions, transparent data, circular use, affordable services and cooperative mechanisms across borders. Water security therefore belongs inside national economic strategy, corporate capital allocation, financial supervision and infrastructure planning.

Keywords: water security, economic security, water scarcity, drought, flood risk, agriculture, food security, energy, data centres, AI infrastructure, semiconductors, trade, finance, transboundary water, water reuse, desalination, climate resilience, water governance.

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Executive Synthesis

The global water challenge is routinely described as a scarcity problem. That description is incomplete. Scarcity is one component of a system that also includes floods, contamination, infrastructure failure, ecosystem degradation, governance, affordability, data quality and the timing of supply. A region with substantial annual rainfall can still face urban shortages because storage, treatment or distribution capacity is weak. A water-scarce economy can remain highly resilient through reuse, desalination, leakage control, diversified sourcing and disciplined allocation. A country with strong municipal supply can still carry material economic exposure if agriculture, power generation or strategic industry depends on stressed basins.

The evidence through September 2026 points to a shift from episodic water shocks toward persistent water volatility. WMO's latest assessment reports a long run of abnormal river-flow conditions and continuing decline in land water storage. (World Meteorological Organization, 2026) This matters because economic systems are designed around expected ranges. Reservoir operating rules, crop calendars, hydropower dispatch, thermal cooling, industrial permits, insurance pricing and municipal infrastructure all rely on historical distributions. As those distributions shift, existing infrastructure and contracts become less reliable even before average annual water availability reaches a formal scarcity threshold.

At the human level, service gaps remain enormous. One quarter of the world's population still lacks safely managed drinking water, and two in five lack safely managed sanitation. (WHO and UNICEF, 2025) These deficits are not separate from productivity. Poor water and sanitation affect health, schooling, labour participation and household time allocation. UN-Water's 2026 World Water Development Report highlights the unequal burden borne by women and girls, including an estimated 250 million hours each day spent collecting water. (UN-Water, 2026) A security framework that focuses only on industrial supply therefore misses a large share of the economic cost.

At the production level, agriculture is the largest direct user of withdrawn freshwater globally. (Food and Agriculture Organization of the United Nations, 2026b) Yet the economic water footprint of food extends through rainfall, soil moisture, groundwater, irrigation, processing, transport and trade. Peer-reviewed work on virtual water trade estimates that roughly one fifth of water used in global food production is embodied in traded products. ('Trends and Environmental Impacts of Virtual Water Trade', 2024) This makes food trade an indirect water-allocation system. Importing grain can reduce pressure on domestic water resources, while dependence on imports from water-stressed regions transfers exposure into supply chains.

Energy systems are also water systems. Hydropower depends directly on hydrological conditions. Thermal generation often relies on cooling water. Fuel extraction and processing require water. Electricity is then required for pumping, treatment, reuse and desalination. Drought-driven hydropower losses have already contributed to higher fossil-fuel generation in multiple regions. (International Energy Agency, 2023, 2025a) The energy transition changes the composition of water demand but does not remove the relationship.

The industrial nexus is widening. Semiconductor fabrication requires high-purity water and elaborate treatment systems. Mining depends on water for processing, dust control and tailings management. Food and beverage manufacturing, chemicals, pharmaceuticals, pulp and paper, textiles and many forms of advanced manufacturing have basin-specific dependencies. Corporate water targets are increasing because water risk is local in a way carbon accounting often is not. A tonne of carbon has similar atmospheric significance regardless of location. A cubic metre of water has radically different economic and ecological significance depending on basin conditions, timing, quality and competing needs.

AI infrastructure makes the point more visible. Data centres are not the largest global water user, but their load is concentrated. Large facilities often seek sites with reliable electricity, cooling conditions, fibre connectivity and rapid permitting. The IEA expects data-centre electricity consumption to more than double between 2024 and 2030. (International Energy Agency, 2025b) Where cooling and electricity generation are water intensive, local water constraints become part of the investment decision. The policy problem is therefore not a global claim that AI is consuming the world's water. It is a local planning question about cumulative demand, cooling design, power mix, wastewater reuse and public acceptance.

Trade exposes another transmission channel. The Panama Canal is a direct example of water security becoming logistics security. A severe 2023-24 drought forced the canal to reduce daily transits and maximum draft, affecting a route that normally carries about 5 percent of global maritime trade. (International Monetary Fund, 2025; Kamali et al., 2024) In 2026, the Canal Authority again reported irregular rainfall and water-management measures linked to El Nino risk. (Panama Canal Authority, 2026) The lesson extends beyond Panama. River levels affect barge transport, floods close ports and roads, drought reduces hydroelectric supply to industrial hubs, and water shortages can change the location economics of factories.

Financial systems are beginning to recognise these links. OECD analysis identifies water-related risks as sources of credit, market, liquidity, underwriting, operational and macroeconomic risk. (OECD, 2025) The challenge is measurement. Water exposure is location specific, dynamic and dependent on sectoral behaviour. Balance-sheet data rarely map cleanly to river basins or aquifers. Corporate disclosure remains uneven. Stress testing is at an early stage. These limitations do not make the risk immaterial. They make measurement capacity part of resilience.

The policy response should avoid a false choice between conservation and infrastructure. Both matter. Demand management without reliable infrastructure leaves societies exposed. Supply expansion without pricing, maintenance and governance often produces rebound demand, financial weakness and environmental damage. The strongest sequence begins with protecting sources and measuring the system, reducing avoidable losses, allocating water toward higher-value and socially essential uses, increasing reuse, diversifying supply, building storage and resilience, and deploying desalination or transfers where local economics and ecology support them.

This study therefore treats water security as a portfolio problem. Resilience comes from source diversity, storage, efficient use, healthy ecosystems, institutional credibility, affordability, data and contingency options. The same principle applies to countries, cities and companies. The objective is not to eliminate dependence on water. That is impossible. The objective is to ensure that water dependence does not become an unmanaged point of economic failure.

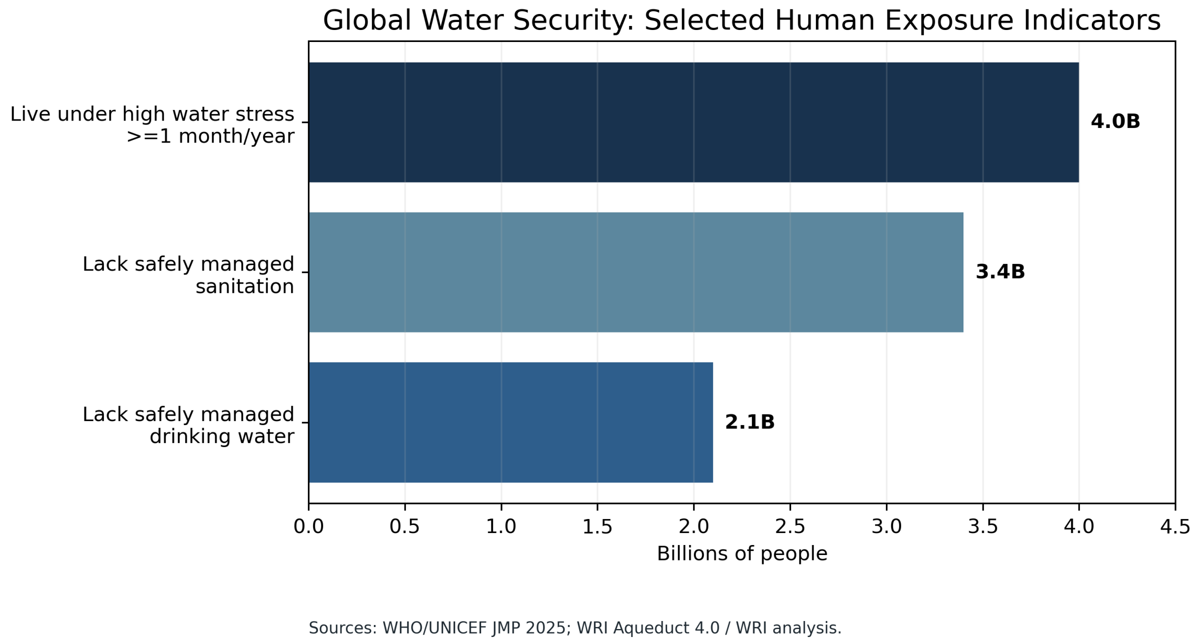

Figure 1: Selected global water-security exposure indicators.

Part I. Research Foundations

Chapter 1

Introduction: Water as an Economic-Security Variable

1.1 The research problem

Economic security is often discussed through energy, food, critical minerals, semiconductors, trade routes, finance and technology. Water runs through each of these systems. Yet water policy is still frequently organised as a specialist infrastructure or environmental field. The result is a mismatch between the physical economy and the institutional map used to manage it.

A modern water-security analysis must begin with four observations.

First, water is location specific. Aggregate national availability can hide local scarcity. A country can have large renewable freshwater resources and still face shortages in major cities or industrial corridors. Basin-level and aquifer-level data therefore matter more than national totals for many operational decisions. WRI explicitly cautions that country rankings are prioritisation tools and should be followed by local analysis. (World Resources Institute, 2026)

Second, quantity and quality are inseparable. A river can carry water that is unusable for drinking, industry or irrigation without treatment. Pollution effectively reduces supply by increasing treatment costs or excluding uses. Water quality also connects upstream and downstream users, which turns wastewater regulation into an economic-allocation question.

Third, timing matters. Annual averages conceal seasonality, drought sequences and flood peaks. Agriculture depends on water during crop-specific windows. Hydropower depends on reservoir levels and inflows. Cities require continuous service. Semiconductor plants and data centres require high reliability. A system that appears adequate on average can fail during critical weeks.

Fourth, water risk propagates through networks. A drought in one basin can affect food prices in importing countries. A flood can stop production at a supplier several tiers upstream. Low river levels can constrain inland freight. Water rationing can reduce factory output and municipal services at the same time. The relevant unit of analysis is therefore not the water sector alone. It is the economic system connected to water.

1.2 Research questions

This monograph addresses eight primary questions.

1. How should water security be defined for economic analysis without reducing it to physical scarcity?

2. Which current indicators best describe the global state of water availability, access, quality and variability?
3. Through which channels do water shocks affect agriculture, energy, industry, cities, technology, trade and finance?
4. Which forms of concentration create the largest strategic exposure?
5. How should governments and firms distinguish chronic stress from acute shocks?
6. Which response options provide the greatest resilience per unit of capital, and under what conditions?
7. How should water risk be incorporated into national economic strategy, corporate investment and financial supervision?
8. Which indicators would provide early warning that a water problem is becoming a broader economic-security problem?

1.3 Central thesis

The central proposition is that water security should be treated as a first-order economic-security capability. The relevant capability is not self-sufficiency in natural water supply. It is the capacity to provide reliable, safe and affordable water for essential human, ecological and productive uses while absorbing droughts, floods, contamination, infrastructure failures and political disputes without disproportionate economic loss.

That definition shifts attention from endowment to system performance. Singapore's natural freshwater conditions differ greatly from those of Canada or Brazil, yet water resilience depends on institutions, source diversification and infrastructure as well as hydrology. The same logic applies at the corporate level. A water-intensive plant in a stressed basin might remain resilient if it uses recycled water, has storage, carries alternative supply agreements and operates under credible allocation rules. A plant in a wetter region might still face high risk if it depends on a single intake or an unreliable utility.

1.4 Scope and evidence cut-off

The evidence cut-off is 20 September 2026. Current conditions are drawn preferentially from WMO, UN-Water, WHO, UNICEF, FAO, WRI, OECD, World Bank, IEA, UNEP, UNECE, IMF and primary corporate disclosures. Peer-reviewed literature is used for Earth-system concepts and virtual water trade. Historical examples are identified as historical rather than treated as current conditions.

The study uses scenarios through 2040. These scenarios are stress tests, not forecasts. No probability is assigned. Their role is to identify dependencies, transmission channels and strategies that perform across different futures.

Chapter 2

Concepts, Definitions and Measurement

2.1 Water scarcity, water stress and water security

Water scarcity is a physical or economic condition in which available water is insufficient to satisfy demand at prevailing quality, location and timing. Water stress is a pressure indicator, often expressed as demand relative to available supply. Water security is broader. It includes the reliability, quality, affordability and governance of water for people, ecosystems and economic activity.

The distinction is operationally important. Water stress indicators are useful screening tools, but they do not predict failure by themselves. High-stress jurisdictions can function well with strong infrastructure and allocation. Low-stress jurisdictions can experience service failure through pollution, underinvestment or extreme events.

WRI's Aqueduct system illustrates this point. Its country and subnational indicators condense hydrological complexity into risk metrics. WRI explicitly states that some indicators, including overall water risk, are not directly measurable and should be supplemented by deeper local analysis. (World Resources Institute, 2026) This monograph therefore uses water-stress rankings as exposure signals, not deterministic outcomes.

2.2 Blue water, green water and the full hydrological cycle

Blue water refers broadly to surface water and groundwater. Green water is the water held in soils and vegetation that supports terrestrial ecosystems and rainfed agriculture. Traditional policy often emphasised withdrawals from rivers and aquifers. Recent Earth-system research shows that soil moisture and evapotranspiration are equally important to climate regulation, ecosystems and food production.

The planetary-boundaries literature now treats freshwater change through both blue and green water. Richardson and colleagues report that both components have moved beyond the proposed safe operating space at the planetary scale. (Richardson et al., 2023) Wang-Erlandsson and colleagues developed the green-water boundary to capture changes in root-zone soil moisture and its role in Earth-system resilience. (Wang-Erlandsson et al., 2022)

This broader frame matters for economics. Irrigation policy cannot fully offset degraded soil moisture, deforestation or rainfall instability. Forest loss can alter regional rainfall recycling. Wetland loss reduces storage and flood buffering. Water security therefore includes land use, soils and ecosystems, not only pipes and reservoirs.

2.3 Withdrawal versus consumption

Withdrawal measures water taken from a source. Consumption measures the portion not returned to the immediate water system because it evaporates, is incorporated into products or crops, or is transferred elsewhere. This distinction is essential when comparing sectors.

FAO reports global withdrawal shares of about 69 percent for agriculture, 19 percent for industry and 12 percent for municipal uses, with major regional variation. (Food and Agriculture Organization of the United Nations, 2026b) These shares should not be confused with consumptive use. Thermal power plants can withdraw large volumes for cooling while returning much of the water, though at different temperatures and qualities. Irrigated agriculture often consumes a larger share through evapotranspiration.

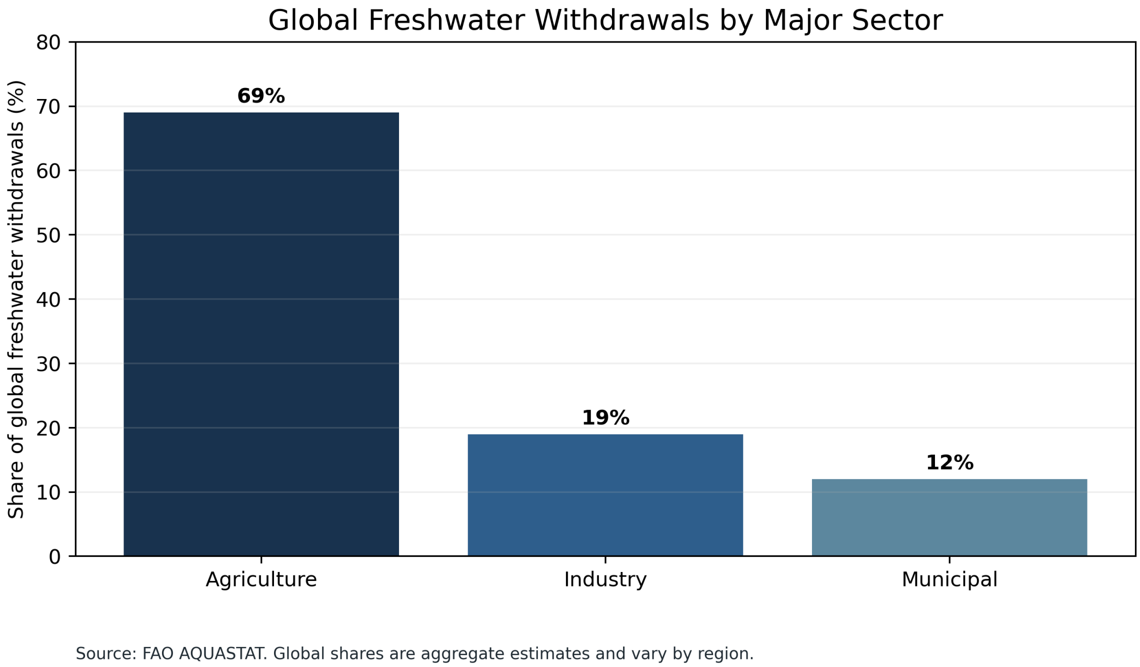

Figure 2.1: Global freshwater withdrawals by major sector.

2.4 Physical, transition and systemic water risk

For economic analysis, water risk is divided here into three categories.

Physical risk includes drought, flood, inadequate quantity, poor quality, salinity, contamination and infrastructure failure.

Transition risk includes changes in tariffs, withdrawal permits, discharge standards, allocation rules, environmental requirements, litigation, disclosure duties and community expectations.

Systemic risk appears when water shocks transmit through multiple sectors or financial institutions. Examples include simultaneous drought impacts on food, electricity, industrial production and inflation, or severe flooding that damages housing, transport and bank collateral across a region.

OECD work increasingly treats water as a financial-stability issue because these transmission channels can affect credit, insurance, asset prices, liquidity and public finances. (OECD, 2025)

Chapter 3

Methodology and Source Hierarchy

3.1 Evidence hierarchy

The study applies a five-level source hierarchy.

Level 1 consists of primary observations and official statistical systems such as WMO hydrological data, WHO/UNICEF service estimates, FAO AQUASTAT, national water agencies and company filings.

Level 2 consists of institutional synthesis and modelling from organizations such as OECD, World Bank, IEA, UN-Water, UNEP and WRI.

Level 3 consists of peer-reviewed research.

Level 4 consists of disclosed corporate operational data used for case-specific evidence. Company claims are treated as self-reported unless independently assured.

Level 5 consists of author-developed frameworks and scenarios. These are clearly labelled as proposals and are not presented as validated indices.

3.2 Treatment of uncertainty

This paper separates five classes of statement: observed data, estimated current conditions, institutional projections, scenario assumptions and original analytical propositions. Numeric values are not combined across models unless units, baselines and definitions are compatible. For example, the World Bank's older regional GDP-loss estimates and the Global Commission's later global and income-group estimates use different modelling approaches and should not be added or interpreted as a single forecast. (Global Commission on the Economics of Water, 2024; World Bank, 2016)

3.3 Geographic resolution

Water risk should ideally be assessed at basin, aquifer, utility-service-area or facility level. National data are used where subnational information is unavailable or where the research question is macroeconomic. The paper repeatedly flags the ecological fallacy risk that arises when country averages are applied to individual assets.

3.4 Research limitations at the outset

Water data contain gaps, inconsistent reporting years and differences in definitions. Groundwater is especially difficult to monitor. Private withdrawals and informal use are often underrecorded. Corporate supply-chain water exposure is difficult to trace beyond direct operations. Climate models disagree on local precipitation outcomes even when they agree on rising hydrological variability. These limits are treated as reasons to improve monitoring rather than reasons to ignore risk.

Part II. The State of Global Water Security

Chapter 4

The Hydrological Baseline in 2026

4.1 A more volatile water cycle

The strongest current global signal comes from WMO's State of Global Water Resources 2025, released on 17 September 2026. The report states that 2025 was one of the driest years for river discharge in 35 years, that the previous seven years produced unusually few rivers with normal flows, that water storage on land has declined over the past decade, and that glaciers lost mass across all regions for a fourth consecutive year. (World Meteorological Organization, 2026)

These observations do not imply uniform global drying. Water risk increasingly involves both too little and too much water. Some regions face drought while others face floods. The same basin can experience both within short intervals. The economic challenge is variability around infrastructure and operating assumptions.

The 2024 WMO assessment had already shown that only one third of river basins experienced normal conditions during that year, with large departures linked to record heat, El Nino and severe regional droughts and floods. (World Meteorological Organization, 2025) The 2025 assessment therefore represents continuation rather than an isolated anomaly.

4.2 Storage is strategic infrastructure

Water storage includes reservoirs, aquifers, wetlands, lakes, soil moisture, snow and glaciers. The World Bank argues for integrated storage planning that combines natural, built and hybrid systems. (World Bank, 2023) This is a critical economic-security insight. Storage creates time. It allows a system to shift water from wet periods to dry periods, to smooth volatility and to preserve essential uses during shocks.

Yet storage is not simply dam capacity. Groundwater overdraft creates hidden liabilities. Reservoirs lose capacity through sedimentation. Wetlands can be drained. Snowpack and glaciers are changing. Urban systems can lose large shares of treated water through leakage. Effective storage therefore requires maintenance, source protection and accounting.

4.3 The cryosphere and downstream dependence

UN-Water's 2025 World Water Development Report focused on mountains and glaciers as water towers. (World Meteorological Organization, 2025) Glacier retreat initially increases runoff in some basins, followed by declining dry-season contribution as ice mass shrinks. The timing differs by basin. For economies dependent on glacier-fed rivers, the issue is not only total annual water. It is seasonal reliability for irrigation, hydropower and cities.

4.4 A dashboard of current risk

Four signals define the current global position. First, hydrological volatility is elevated. Second, service deficits remain large. Third, water stress is concentrated in many economically important regions. Fourth, ecosystem degradation is reducing natural resilience. Together they create a system in which physical shocks and institutional weaknesses reinforce each other.

Chapter 5

Access, WASH and Human Capital

5.1 Service access remains a macroeconomic issue

WHO and UNICEF estimate that global safely managed drinking-water coverage increased from 68 percent in 2015 to 74 percent in 2024. Safely managed sanitation increased from 48 percent to 58 percent. Basic hygiene coverage rose from 66 percent to 80 percent. (WHO and UNICEF, 2025) Progress is substantial, yet the remaining gaps are large in absolute numbers because the global population has also grown.

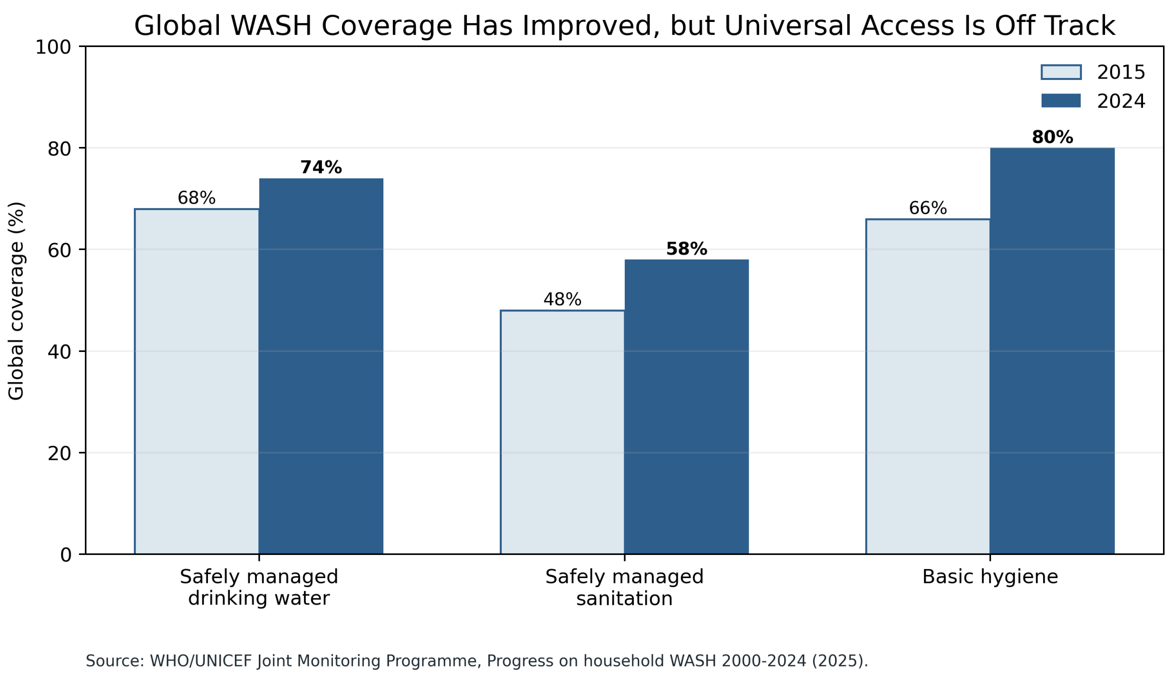

Figure 5.1: Global WASH coverage, 2015 and 2024.

In 2024, 2.1 billion people lacked safely managed drinking water and 3.4 billion lacked safely managed sanitation. (WHO and UNICEF, 2025) These figures describe service quality, availability and safety, not merely the existence of an improved source or toilet. The distinction matters because infrastructure access without reliable quality does not fully protect health or productivity.

5.2 Human capital channels

Unsafe water and sanitation raise disease burden and reduce labour productivity. Time spent collecting water reduces time available for paid work, education and care. UN-Water's 2026 report estimates that women and girls spend roughly 250 million hours per day collecting water. (UN-Water, 2026) The macroeconomic effect is difficult to measure precisely because it includes health, time, school attendance and gender inequality, but the direction is clear.

WHO's 2026-2035 WASH strategy states that unsafe WASH conditions still contribute to at least 1.4 million preventable deaths each year. (World Health Organization, 2026) These losses are not captured by conventional water-sector revenue metrics. They are social and economic costs arising from service failure.

5.3 Utility finance and non-revenue water

UN-Water and WHO reported in 2026 that, among participating countries with data, the average funding gap between identified WASH needs and available funding was 46 percent, while non-revenue water averaged 39 percent. (World Health Organization, 2026) Non-revenue water includes physical leakage and commercial losses. High levels weaken utilities financially and waste treatment, pumping and source capacity.

The policy implication is that new supply alone is often an inefficient response. Repairing networks, improving metering and strengthening billing can create effective supply at lower marginal cost than major new infrastructure. The local answer depends on system conditions.

Chapter 6

Water Stress, Groundwater and Ecosystems

6.1 Stress is widespread but uneven

WRI's Aqueduct analysis identifies 25 countries with extremely high annual water stress, together home to around one quarter of the global population. It also estimates that at least half of the world's population lives under highly water-stressed conditions for at least one month each year. (Kuzma et al., 2023) These statistics describe exposure, not inevitable shortage. High-stress regions differ greatly in institutional capacity and supply diversification.

The current 2026 Aqueduct dataset provides baseline and future rankings to 2080 under multiple climate scenarios. WRI cautions that the indicators are condensed from basin-level data and that overall water risk is a prioritisation tool rather than a directly validated measurement. (World Resources Institute, 2026)

6.2 Groundwater as hidden strategic reserve

Groundwater stabilises agriculture, cities and industry during dry periods, but this stabilisation function can conceal depletion. When pumping exceeds recharge, groundwater levels fall, pumping costs rise, land can subside and wells can fail. Because aquifers are underground and monitoring networks are incomplete, financial and policy systems often detect the problem late.

Groundwater therefore resembles a strategic reserve that can be depleted without appearing on conventional fiscal balance sheets. A country might record agricultural output growth while its underlying aquifer asset is declining. National wealth accounting should record this depletion where data permit.

6.3 Freshwater ecosystems as infrastructure

UNEP reported in 2024 that 90 countries were experiencing degradation in one or more types of freshwater ecosystem. River flow had declined significantly in 402 basins, and surface water bodies were shrinking or disappearing in 364 basins. (United Nations Environment Programme, 2024) Ecosystem degradation increases the cost of engineered systems by reducing natural filtration, storage, flood buffering and groundwater recharge.

The correct comparison is not nature versus infrastructure. Wetlands, floodplains, forests and soils are infrastructure in an economic sense because they provide services with replacement costs. The strongest water-security portfolios combine ecological and engineered assets.

Chapter 7

Climate Change, Extremes and Non-Stationarity

7.1 The failure of historical stationarity

Water infrastructure has traditionally been designed using historical hydrological distributions. Climate change weakens the assumption that the statistical properties of the past remain stable. Higher temperatures alter evaporation, snowpack, soil moisture and crop demand. Changes in atmospheric circulation alter rainfall intensity and seasonality. Sea-level rise increases salinity risks in coastal aquifers and deltas.

The result is non-stationarity. A design standard based on a one-in-one-hundred-year historical flood might not retain the same probability in the future. A reservoir yield model based on twentieth-century inflows might overstate reliability. Investment appraisal therefore needs climate-adjusted operating ranges rather than a single expected value.

7.2 Drought and flood are not opposites in planning terms

A resilient basin must manage both. Drought planning emphasises storage, demand management and allocation. Flood planning emphasises drainage, retention, floodplains and emergency response. Some interventions support both objectives. Wetland restoration, soil improvement and upstream retention can increase infiltration and reduce flood peaks while supporting dry-season flows.

7.3 Climate adaptation is water adaptation

The World Bank's High and Dry analysis estimated that water scarcity under climate change could reduce GDP by as much as 6 percent in some regions by 2050 absent better management. (World Bank, 2016) More recent modelling by the Global Commission and cited by OECD places potential long-run losses around 8 percent of global GDP and 10-15 percent in low-income countries under severe water insecurity. (Global Commission on the Economics of Water, 2024; OECD, 2026) These estimates differ in methods and should not be compared as a time series. Their common message is that water is a macroeconomic variable.

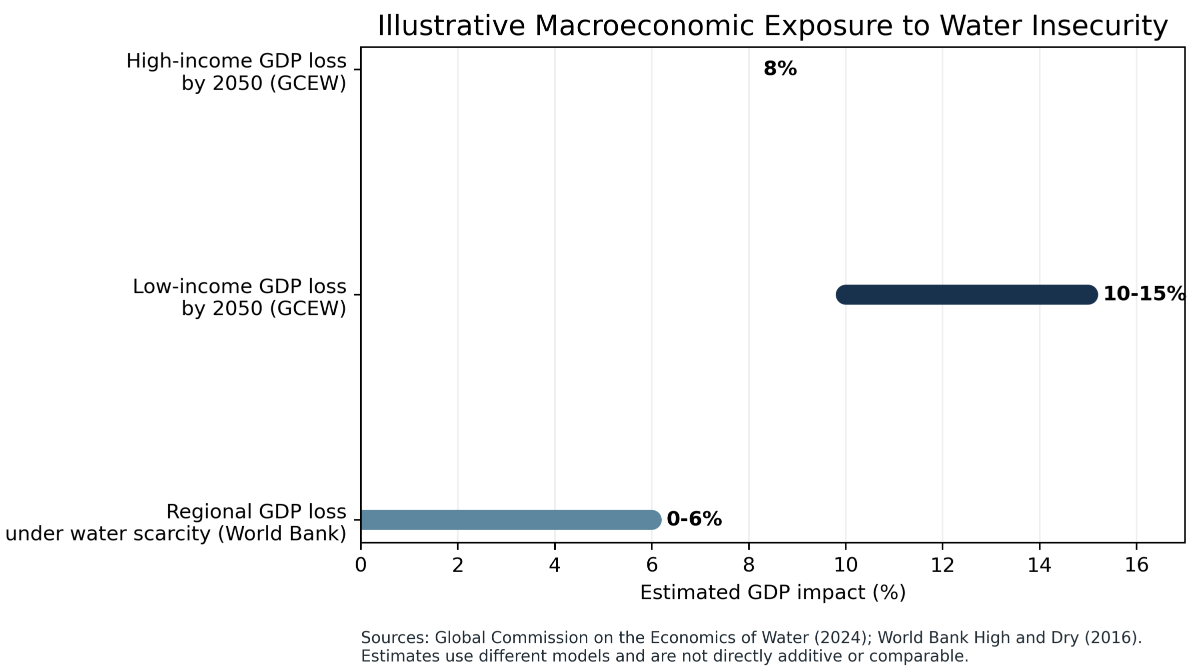

Figure 7.1: Selected estimates of macroeconomic exposure to water insecurity.

Part III. Economic Transmission Channels

Chapter 8

Food, Agriculture and Virtual Water

8.1 Agriculture as the dominant direct water user

Agriculture is the largest user of withdrawn freshwater globally. FAO's aggregate estimate assigns about 69 percent of withdrawals to agriculture, 19 percent to industry and 12 percent to municipalities. (Food and Agriculture Organization of the United Nations, 2026b) A more recent FAO water-scarcity page places agriculture above 70 percent of global freshwater withdrawals and states that roughly 1.2 billion people live in agricultural areas facing severe water constraints. (Food and Agriculture Organization of the United Nations, 2026a) The difference reflects source vintages and definitions, not a contradiction in the underlying conclusion that agriculture dominates global withdrawals.

The economic importance of agricultural water is larger than the direct withdrawal share suggests. Irrigated land produces a disproportionate share of food output. Rainfed agriculture depends on green water, particularly root-zone soil moisture and rainfall timing. Livestock depends on feed crops, drinking water and processing. Food manufacturing adds further water demand. Drought therefore affects food systems through both blue and green water.

8.2 Yield risk and food-price transmission

Water shocks affect food prices when production losses occur in regions that supply large shares of internationally traded crops. The effect depends on inventories, substitution, trade policy and whether shocks occur simultaneously across exporting regions. A drought in one country need not create a global food crisis. Correlated drought across several exporters, combined with export restrictions, creates a far larger risk.

OECD's 2025 financial-stability work cites evidence that crop yields in particularly dry years can decline by up to 22 percent, while longer drought duration can reduce production of major crops. (OECD, 2025) These figures should be interpreted as study-specific effects rather than universal yield coefficients. The policy implication is to stress-test food systems against spatially correlated water shocks rather than rely on average global production.

8.3 Virtual water trade

Trade transfers water demand across borders through goods. Peer-reviewed work in Nature Reviews Earth & Environment estimates that roughly 20 percent of water used in global food production is embodied in traded food, and that virtual-water trade increased substantially between 1986 and 2022. ('Trends and Environmental Impacts of Virtual Water Trade', 2024) This makes trade a water-management mechanism and a risk-transmission channel.

A water-scarce country importing wheat is effectively importing the water used to grow that wheat. This can protect domestic aquifers. Yet dependence on water-intensive imports from stressed exporting regions creates indirect exposure. Strategic food policy therefore needs to consider both caloric dependence and the hydrological risk of supplier regions.

8.4 Agricultural adaptation hierarchy

Agricultural water resilience begins with crop choice, soil management, irrigation efficiency, scheduling and loss reduction. Technology is useful when incentives support efficient use. Efficiency gains alone do not guarantee lower basin withdrawals because saved water can be used to expand irrigated area. This rebound effect is one reason allocation institutions matter.

The strongest adaptation package combines field-level efficiency with basin-level caps, groundwater monitoring, drought-tolerant crops, insurance design, storage, weather information and trade options. The objective is not maximum local production at any water cost. It is reliable food availability with sustainable water use.

Chapter 9

Energy and Power Systems

9.1 Water for energy, energy for water

Water and energy form a two-way dependency. Electricity is needed for pumping, treatment, distribution, wastewater processing, reuse and desalination. Water is needed for hydropower, cooling, fuel extraction, refining, bioenergy and parts of the clean-energy supply chain.

The economic risk appears when both systems are stressed at once. A heatwave raises electricity demand for cooling while increasing evaporation and water demand. Drought reduces hydropower and can constrain thermal cooling. If electricity becomes scarce, water utilities face higher operating risk. A failure in either network can therefore amplify the other.

9.2 Hydropower exposure

The IEA reported that global hydropower generation fell sharply in 2023 because of droughts and below-average rainfall, then recovered in 2024. (International Energy Agency, 2025a) In the first half of 2025, drought conditions reduced hydropower output in several regions. The pattern shows that installed capacity is not equal to firm energy. Hydrological conditions determine actual output.

Countries with large hydro shares need diversified generation, storage, interconnection and drought-aware reservoir rules. This does not diminish the value of hydropower. It means hydropower should be planned as a climate-sensitive asset rather than a fixed-output resource.

9.3 Thermal generation and cooling water

Thermal power plants often withdraw water for cooling. During droughts and heatwaves, intake volumes can fall and discharge-temperature limits can constrain operation. The IEA has documented examples in Europe, India and other regions where water scarcity or high river temperatures reduced thermal output. (International Energy Agency, 2023)

Cooling technologies differ. Once-through systems withdraw more water but consume less than evaporative cooling. Closed-loop systems reduce withdrawals but consume more through evaporation. Dry cooling reduces water use but can increase cost and reduce efficiency during hot weather. Technology choice should therefore be basin specific.

9.4 Water infrastructure as electricity demand

Desalination and advanced treatment provide reliable supply but require electricity. Pumping water over long distances or elevations is also energy intensive. The future water system therefore depends on grid capacity and energy prices. Low-carbon electricity can reduce the emissions footprint of desalination and reuse, but electricity security remains an operating requirement.

Chapter 10

Industry, Manufacturing and Strategic Supply Chains

10.1 Water as a production input

Industrial water risk is heterogeneous. Some facilities use water directly in products. Others use it for cleaning, cooling, steam, chemical reactions, dust suppression, mineral processing or environmental control. The critical variable is often not total annual volume. It is the purity specification and the tolerance for interruption.

A factory that requires high-purity water can face operational shutdown even when municipal water remains available. A mine can have ample gross water access but still face risk from tailings, seasonal variability or community allocation disputes. An industrial park can become constrained by wastewater-discharge capacity before raw-water supply is exhausted.

10.2 Semiconductor manufacturing

Semiconductor fabrication is a strategic example because advanced manufacturing requires ultra-pure water. Intel states that the majority of its direct water use occurs in operations and that water is used throughout manufacturing, cooling and support systems. The company reported conserving roughly 11.2 billion gallons of water through operational and community initiatives in 2025. (Intel Corporation, 2026)

TSMC reported in its 2025 annual reporting that water-saving measures conserved 6.73 million cubic metres across its system and that several Taiwan fabs achieved platinum-level Alliance for Water Stewardship certification. (Taiwan Semiconductor Manufacturing Company, 2026) These figures are company disclosures rather than independent estimates, but they show how water resilience has entered semiconductor operating strategy.

The supply-chain implication is significant. Advanced chip production is geographically concentrated. If water stress affects a major fabrication cluster, the shock can transmit globally through electronics, vehicles, industrial equipment and AI infrastructure. Semiconductor resilience therefore depends on water alongside electricity, chemicals, equipment, talent and logistics.

10.3 Mining and materials

Mining operations require water for mineral processing, dust control and other functions, with large variation by commodity, ore body and process. Water is also central to tailings management and environmental performance. Climate variability can create both shortage and excess-water risk at mines.

The strategic-minerals transition therefore has a water dimension. New mines and refineries may be located in arid or seasonally stressed regions. Project evaluation should consider basin-level water availability, community needs, cumulative industrial demand and climate scenarios before capital is committed.

10.4 Manufacturing location decisions

Water has historically been treated as a low-cost utility in many investment models. This assumption is becoming less reliable. Site selection for water-sensitive industries should include source diversity, drought history, water rights, tariff structure, treatment capacity, discharge rules, utility financial health, flood risk and competing demand.

Water is unlikely to replace labour, power, logistics and market access as the dominant location factor across all industries. In high-dependence sectors, it is increasingly a constraint that can disqualify otherwise attractive sites.

Chapter 11

Artificial Intelligence and Data Centres

11.1 The local water effect of a global digital system

AI infrastructure is a useful case study because it brings electricity, cooling, capital and local resource allocation into the same planning problem. Data centres are not a leading global water user compared with agriculture, yet large facilities are spatially concentrated and can create material local demand.

The IEA estimated global data-centre electricity use at about 415 TWh in 2024. Its 2025 Energy and AI report projects more than 1,000 TWh by 2030 in the base case. (International Energy Agency, 2025b) The IEA's 2026 update reports continued rapid investment and expansion of AI-focused data-centre capacity. (International Energy Agency, 2026)

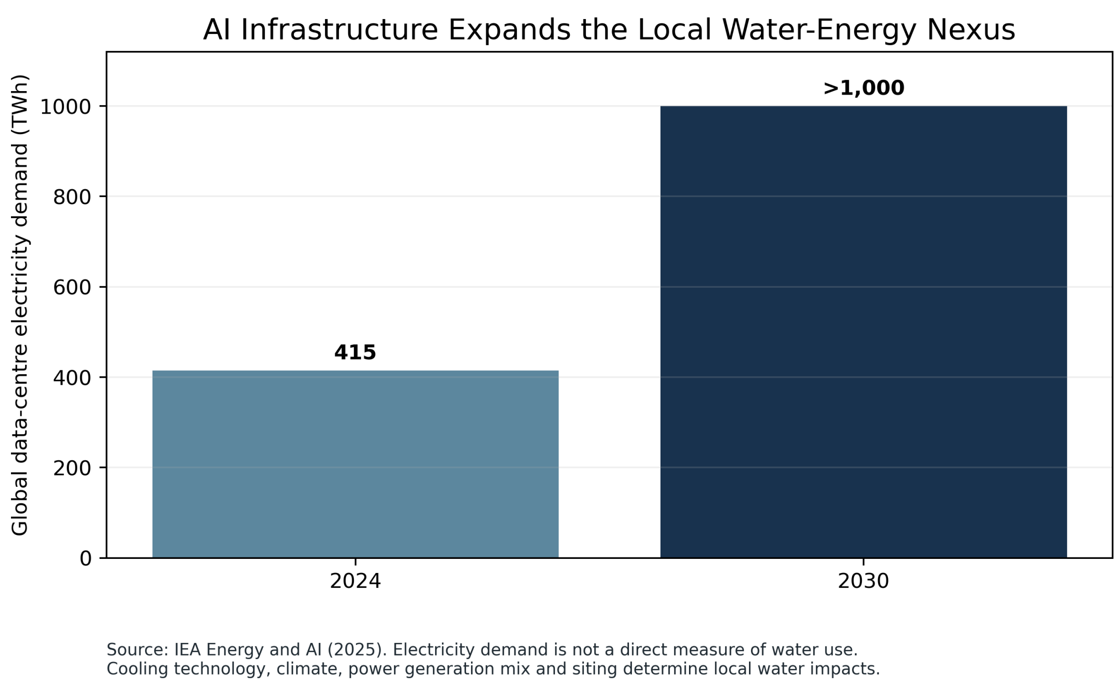

Figure 11.1: Data-centre electricity demand and the local water-energy nexus.

Electricity use is not a direct proxy for water consumption. Water outcomes depend on cooling systems, climate, water source, whether water is recycled, and the generation mix supplying electricity. A data centre cooled primarily with air or closed-loop systems has a different local water profile from one using evaporative cooling. A data centre supplied by water-intensive thermal power has indirect water exposure even if on-site withdrawals are low.

11.2 Technology and design

Microsoft reports that direct-to-chip cooling can save more than 125 million litres of water per facility per year compared with earlier approaches. It also reports a reuse partnership in Quincy, Washington that reduced potable-water use at its operations in the region by 97 percent. (Microsoft, 2025) These company-reported examples demonstrate that design choices can materially change local water intensity.

11.3 Policy questions for AI infrastructure

The policy question should not be framed as whether data centres are good or bad for water. The relevant questions are site specific. Is the basin stressed? Is reclaimed water available? What is the cooling design? What electricity mix supplies the facility? What happens during drought? Does the project compete with drinking water, agriculture or ecosystems? Are cumulative projects assessed together?

A robust permitting framework should require water-demand disclosure, drought operating plans, source-quality specifications, reuse feasibility, basin-level cumulative assessment and public reporting of actual performance. This allows investment without treating local water as an unlimited external input.

Chapter 12

Cities, Housing and Public Health

12.1 Urban concentration of demand

Urban water security depends on source reliability, treatment capacity, network condition, storage, drainage, sanitation and utility finance. Rapidly growing cities face a difficult sequence. Demand rises before infrastructure catches up, informal settlements expand beyond networks, and climate extremes expose drainage and source vulnerabilities.

The World Bank notes that urban water scarcity is expected to intensify and that cities need a mix of conventional and unconventional sources. (World Bank, 2025b) Water reuse, leakage reduction, stormwater capture and desalination are increasingly part of urban portfolios.

12.2 Affordability and utility solvency

Water is both a human right and a service requiring infrastructure, energy, chemicals, staff and maintenance. Tariffs that are too high exclude poor households. Tariffs that are structurally below operating cost can weaken utilities and reduce service quality. The policy problem is therefore not simply whether water should be priced. It is how to recover efficient costs while protecting low-income households through targeted support.

OECD's 2026 financing report argues that underpricing and weak revenue structures often prevent utilities from covering operation and maintenance, contributing to deterioration and underperformance. (OECD, 2026)

12.3 Flood risk in cities

Urban water risk also includes excess water. Flooding damages housing, transport, power networks and commercial property. Impervious surfaces increase runoff. Informal housing often expands into floodplains. Drainage systems designed for historical rainfall can be overwhelmed by more intense storms.

Urban resilience therefore requires land-use rules, drainage, retention, floodplain protection, insurance, early warning and emergency planning alongside drinking-water investment.

Chapter 13

Trade, Logistics and the Water Footprint of Globalization

13.1 Water as a trade-route constraint

Water affects global trade directly through canals and navigable rivers. The Panama Canal offers the clearest recent example. The IMF noted that a severe drought in 2023-24 forced reductions in daily transits and maximum draft. The canal normally carries about 5 percent of global maritime trade. (International Monetary Fund, 2025; Kamali et al., 2024)

The Panama Canal Authority reported in 2026 that irregular rainfall and El Nino risk again required water-conservation measures and draft adjustments. The canal also supplies water to more than half of Panama's population, creating a direct allocation link between domestic supply and global logistics. (Panama Canal Authority, 2026)

This is a strategic lesson. A trade chokepoint can depend on the same freshwater resource used by households and power systems. Resilience therefore requires integrated basin planning rather than treating shipping water and drinking water as separate sectors.

13.2 Rivers as industrial transport corridors

Low river levels can limit barge loads and increase transport costs. The IEA has highlighted the 2022 European drought, when low water levels in rivers including the Rhine constrained movement of coal, chemicals and other materials. (International Energy Agency, 2023) Floods create the opposite problem by closing ports, roads and rail links.

13.3 Virtual water and trade strategy

Trade also redistributes water demand through products. Virtual-water analysis shows that agriculture dominates embodied water flows. ('Trends and Environmental Impacts of Virtual Water Trade', 2024) From an economic-security perspective, this means trade diversification should consider hydrological concentration. A food importer dependent on several suppliers in the same drought-prone climate system is less diversified than a conventional country count suggests.

Chapter 14

Financial Stability, Sovereign Risk and Capital Allocation

14.1 From environmental risk to financial risk

OECD analysis identifies several transmission channels from water to finance. Drought reduces output and incomes. Floods damage collateral and infrastructure. Water-quality failures create liability and remediation costs. Stranded assets can emerge when extraction permits are tightened or water sources become unreliable. Insurance losses and public reconstruction costs then shift risk across balance sheets. (OECD, 2025)

These risks become systemic when multiple borrowers share exposure to the same basin, crop, utility or urban floodplain. Conventional sector diversification may fail if underlying water exposure is correlated.

14.2 Water and sovereign risk

Sovereign exposure arises through public infrastructure costs, disaster response, agricultural support, utility subsidies, food imports and lost tax revenue. Water shocks can also increase inflation through food and electricity prices. Countries with limited fiscal space may delay maintenance, increasing future vulnerability.

A water-security balance sheet should therefore include natural assets, engineered infrastructure, utility liabilities and contingent disaster exposure. Few governments currently present these items in one place.

14.3 Investment returns and financing gaps

The economic case for water investment is strong but difficult to monetise. OECD's 2026 Financing Water Security report cites estimates that each dollar invested in water and sanitation generates around four dollars in benefits through health, education, food security and environmental outcomes. (OECD, 2026) Earlier OECD work estimated large annual losses from inadequate water and sanitation, flooding and irrigation insecurity, while placing the investment need for SDG 6 above one trillion dollars per year. (OECD, 2022)

Water projects often struggle because benefits accrue across many sectors while revenue is collected by one utility. This creates a financing mismatch. A flood-control wetland might protect roads, homes, insurers and businesses, but no single beneficiary captures the full benefit. Public finance, blended finance and outcome-based instruments are therefore important where private cash flow alone is insufficient.

Part IV. Geopolitics, Governance and Rights

Chapter 15

Transboundary Water and Strategic Interdependence

15.1 Shared basins are the norm

Most freshwater systems do not follow political borders. UNECE and UNESCO report that 153 countries rely on transboundary waters. Only 28 percent of those countries had effective arrangements covering most of their shared waters in the latest reporting cycle. (UNECE and UNESCO, 2024)

This gap matters because climate change alters flows, timing and extremes. Agreements designed around historical conditions may face pressure when available water falls, when flood risks increase or when new infrastructure changes upstream-downstream relationships.

15.2 Cooperation as infrastructure

Transboundary institutions are a form of infrastructure. They create rules for data sharing, allocation, pollution, drought and flood response. UNECE reported that parties to the Water Convention operate through more than one hundred joint institutions, many covering data exchange, pollution, allocation and extremes. (United Nations Economic Commission for Europe, 2024)

The value of such institutions is highest before crisis. Once a drought becomes acute, political incentives narrow. Pre-agreed procedures reduce uncertainty and give technical agencies a channel for coordination.

15.3 Water conflict narratives require caution

Water stress can intensify existing political tensions, but scarcity does not mechanically cause interstate war. Cooperation is common because shared water creates repeated interaction and mutual dependence. The risk rises where institutions are weak, allocation is contested, data are disputed and other political conflicts already exist.

A rigorous water-security paper should therefore avoid deterministic claims that future wars will be fought over water. The more defensible statement is that water stress acts as a threat multiplier and bargaining variable in some contexts.

Chapter 16

Domestic Allocation, Rights and Political Economy

16.1 Allocation is the core scarcity decision

When supply is limited, every water system allocates, explicitly or implicitly. Allocation can occur through permits, quotas, prices, priority rules, infrastructure access, historical rights or political bargaining. The absence of formal allocation does not mean there is no allocation. It often means access is determined by power, location or pumping capacity.

16.2 The human right and economic allocation

Domestic systems need to protect basic human needs while allocating additional water across agriculture, ecosystems and industry. This creates difficult trade-offs. Water pricing can support efficiency, but price alone is not sufficient where rights, monopoly utilities and social needs are involved.

The Global Commission on the Economics of Water argues for better valuation and reduced underpricing while protecting equity. (Global Commission on the Economics of Water, 2023, 2024) The core principle is that low-income households should not bear the cost of correcting wasteful industrial or agricultural allocation.

16.3 Agricultural subsidies and incentives

The Global Commission has criticised subsidies that encourage inefficient water use. (Global Commission on the Economics of Water, 2023) Reform is politically difficult because subsidies support farmer incomes and food affordability. A credible transition therefore needs sequencing, income support and productivity investment rather than abrupt withdrawal.

Part V. Technology, Infrastructure and Investment Responses

Chapter 17

A Water Security Response Hierarchy

Water systems need portfolios rather than single solutions. The response hierarchy used in this paper begins with source protection and measurement, then moves through demand reduction, reallocation, reuse, diversification, storage and new supply. Desalination appears later in the hierarchy because it is valuable in the right setting but carries energy, cost and brine-management requirements.

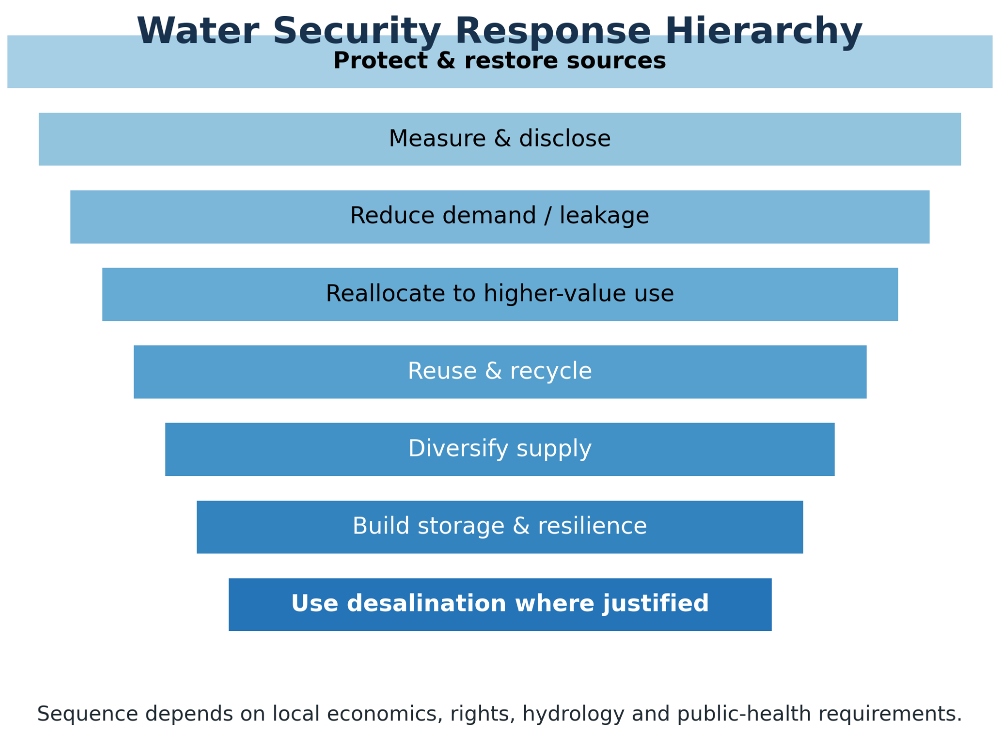

Figure 17.1: A response hierarchy for water security.

The order is not universal. An island state with limited freshwater may rationally rely heavily on desalination. A leaking city should first capture losses. An agricultural basin with depleted groundwater may need enforceable abstraction limits before efficiency investment produces durable savings.

Chapter 18

Storage, Watersheds and Nature-Based Infrastructure

18.1 Integrated storage

The World Bank advocates a broader concept of storage that includes reservoirs, aquifers, wetlands, soil moisture and other natural and built systems. (World Bank, 2023) This approach is economically sound because resilience depends on total system capacity, not the category of asset.

18.2 Nature-based solutions

Wetlands, floodplains, forests and healthy soils slow runoff, filter pollutants and support groundwater recharge. These benefits are site specific and should not be oversold as substitutes for all engineered infrastructure. In many basins they are complements that reduce the required size or operating cost of hard infrastructure.

18.3 Maintenance before expansion

Water assets have long lives and high fixed costs. Deferred maintenance creates hidden liabilities. Pipe leakage, pump inefficiency, sedimentation and treatment failures reduce effective capacity. Capital planning should therefore compare rehabilitation with expansion on a lifecycle basis.

Chapter 19

Efficiency, Demand Management and Agricultural Reform

19.1 Efficiency is necessary but not sufficient

Water-efficiency technology reduces use per unit of output. Basin withdrawals fall only if savings are not fully absorbed by expanded activity. This is why efficiency programmes should be paired with allocation rules and monitoring where scarcity is binding.

19.2 Urban demand management

Smart metering, pressure management, leakage detection, appliance standards and tariff design reduce avoidable use. During droughts, temporary restrictions and tiered pricing can protect essential supply. Public legitimacy matters. Restrictions perceived as unfair are harder to sustain.

19.3 Agricultural productivity per unit of water

Agricultural policy should optimise economic and nutritional value per unit of water rather than maximise hectares irrigated. Crop switching, deficit irrigation, scheduling, protected agriculture and soil improvement can raise water productivity. The correct mix depends on climate, markets and farmer capacity.

Chapter 20

Water Reuse and Circular Systems

20.1 Wastewater as a resource

The linear model of extracting freshwater, using it once and discharging wastewater is increasingly costly in water-stressed regions. The World Bank's 2025 work on reuse argues that treated wastewater can provide reliable supply for municipal and industrial uses when enabling regulation, pricing and project structures exist. (World Bank, 2025c)

A World Bank analysis notes that more than 80 percent of wastewater globally is discharged without treatment. (World Bank, 2025a) The estimate varies by methodology and country coverage, but the scale indicates large potential for improved treatment and reuse.

20.2 Fit-for-purpose treatment

Not every use requires drinking-water quality. Industrial cooling, landscaping, agriculture and some process uses can use treated water to fit-for-purpose standards. This reduces treatment energy and preserves high-quality freshwater for drinking and sensitive processes.

20.3 Barriers to reuse

Reuse projects face public acceptance, regulation, pipeline costs, quality assurance and pricing challenges. The strongest business case occurs where wastewater is located near large users. (World Bank, 2025c)

Chapter 21

Desalination and New Water

21.1 A strategic option with trade-offs

Desalination provides a climate-independent source where seawater or brackish water is accessible. Falling membrane costs and improved energy efficiency have expanded deployment. The World Bank's New Water initiative treats desalination and reuse as increasingly important elements of water portfolios. (World Bank, 2025b)

The constraints are energy use, capital cost, brine disposal and marine impacts. Renewable electricity can lower operational emissions but does not eliminate environmental or financial considerations.

21.2 The portfolio principle

Desalination is strongest as part of a diversified portfolio rather than a substitute for governance. A city that builds desalination while allowing extreme leakage or unsustainable groundwater pumping might add expensive supply without correcting structural problems.

Chapter 22

Digital Water, Monitoring and Artificial Intelligence

22.1 Data is infrastructure

Water allocation depends on measurement. Many basins lack timely data on withdrawals, aquifer levels, leakage, quality and ecosystem conditions. WMO's 2026 report notes improvement in data availability but continued gaps, especially in heavily affected areas. (World Meteorological Organization, 2026)

Sensors, satellite observations, smart meters and digital twins increase visibility. AI can improve leak detection, demand forecasting, treatment control and flood prediction. These tools need institutional capacity and data governance. Poor data fed into sophisticated models produces false precision.

22.2 Open data and trust

Water disputes often intensify when parties disagree about basic facts. Public hydrological data, transparent allocation rules and auditable corporate reporting reduce information asymmetry. Data governance is therefore a trust mechanism as well as a technical function.

Chapter 23

Financing Water Security

23.1 Why water is difficult to finance

Water assets often have public-good characteristics, long payback periods and politically constrained tariffs. Benefits extend beyond the paying customer. Flood protection, ecosystem restoration and sanitation produce health and resilience gains that do not appear fully in utility cash flow.

OECD's 2026 financing work argues that structuring finance matters as much as increasing volume. It highlights bond finance, Islamic finance, results-based structures and public-private partnerships, while stressing that risk allocation and long-term service performance are more important than transaction form. (OECD, 2026)

23.2 A financing stack

A resilient financing stack has five layers: public funding for rights and public goods, utility revenue for operations and maintenance, concessional capital for projects with large social benefits, commercial finance for bankable assets, and risk-sharing tools for climate and demand uncertainty.

23.3 Financial supervision

Banks and insurers need exposure mapping that links borrowers and collateral to basins and flood zones. Water-risk supervision should avoid imposing a single global stress coefficient. Risk varies by geography, source, sector and adaptation capacity. (OECD, 2025)

Part VI. Original Analytical Frameworks

Chapter 24

Water Security Systems Framework

The Water Security Systems Framework developed in this paper treats national and regional resilience as the interaction of twelve domains.

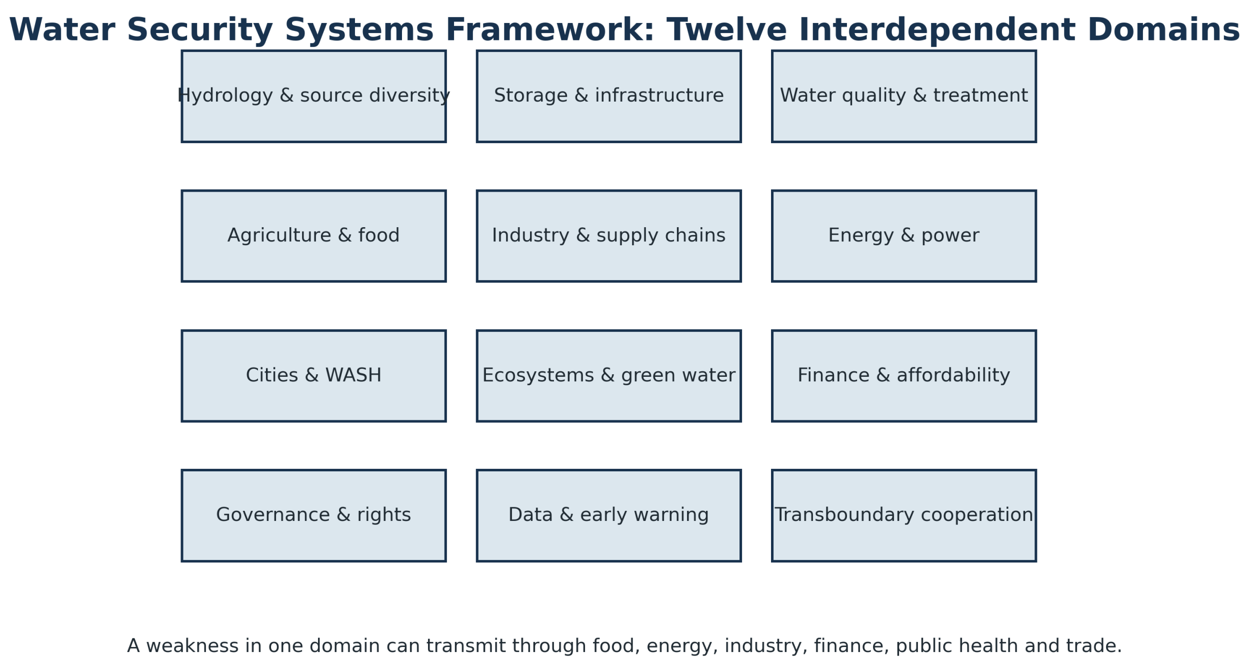

Figure 24.1: The twelve-domain Water Security Systems Framework.

The domains are deliberately broad. Hydrology alone does not determine resilience. Storage without source protection can fail. Infrastructure without utility finance deteriorates. Agriculture without basin allocation can deplete aquifers. Data without governance does not change behaviour. Transboundary cooperation without domestic implementation can remain symbolic.

24.1 Domain 1: Hydrology and source diversity

Measures renewable supply, drought variability, groundwater condition, rainfall dependence and the number of independent sources available to major users.

24.2 Domain 2: Storage and infrastructure

Measures reservoirs, aquifer storage, network condition, treatment capacity, redundancy and maintenance quality.

24.3 Domain 3: Water quality and treatment

Measures source contamination, treatment reliability, industrial discharge, salinity and wastewater management.

24.4 Domain 4: Agriculture and food

Measures water productivity, irrigation efficiency, crop exposure, groundwater dependence and food-import diversification.

24.5 Domain 5: Industry and supply chains

Measures dependence of strategic industries, availability of recycled water, supplier-basin exposure and business continuity.

24.6 Domain 6: Energy and power

Measures hydropower exposure, cooling-water dependence, electricity reliability for water systems and energy intensity of new water sources.

24.7 Domain 7: Cities and WASH

Measures safely managed access, leakage, storage, sanitation, affordability, drainage and drought planning.

24.8 Domain 8: Ecosystems and green water

Measures wetland condition, watershed protection, soil moisture, land-use pressure and environmental-flow protection.

24.9 Domain 9: Finance and affordability

Measures utility solvency, capital access, household affordability, insurance availability and fiscal exposure.

24.10 Domain 10: Governance and rights

Measures allocation clarity, enforcement, human-rights protection, tariff institutions, permit quality and dispute resolution.

24.11 Domain 11: Data and early warning

Measures hydrological monitoring, groundwater data, metering, public reporting, forecasting and data interoperability.

24.12 Domain 12: Transboundary cooperation

Measures agreements, joint institutions, data exchange, drought protocols, flood coordination and dispute mechanisms.

Chapter 25

Water Security Resilience Index

25.1 Proposed construction

The proposed Water Security Resilience Index, or WSRI, is an analytical framework rather than a validated global ranking. Each of the twelve domains is scored from 0 to 100. The overall score uses a geometric mean:

$$WSRI = \left(\prod_{i=1}^{12} D_i \right)^{1/12}$$

where D_i is the score for domain i.

The geometric mean is used because water security has weak-link properties. A country with excellent infrastructure but severe governance failure should not receive the same score as a country with balanced strength across domains. The geometric mean penalises extreme weakness more than an arithmetic average.

25.2 Minimum-domain override

A second rule is proposed. If any domain falls below 25, the system should be classified as carrying a critical vulnerability regardless of the overall index. This prevents an average score from obscuring a failure point.

25.3 Validation agenda

The WSRI should be tested against observed outcomes such as drought-related GDP loss, duration of urban rationing, industrial shutdowns, flood recovery times and food-price volatility. It should not be used for policy ranking until weights, indicators and thresholds are empirically tested.

Chapter 26

Strategic Water Exposure Score for Assets

For a company, project or facility, this paper proposes a Strategic Water Exposure Score, or SWES:

$$SWES = 100 \times (D \times S \times C \times R)^{1/4}$$

where:

- D is operational dependence on water, scaled 0 to 1.
- S is source stress and variability, scaled 0 to 1.
- C is concentration of water sources and critical upstream suppliers, scaled 0 to 1.
- R is recovery difficulty, including switching time and replacement options, scaled 0 to 1.

A high score indicates strategic exposure, not expected loss. The framework forces decision-makers to separate direct water intensity from the resilience of supply.

Chapter 27

Water-Adjusted Capital Allocation

Capital budgeting should include water risk as a scenario-adjusted cash-flow variable. A simplified decision metric is:

$$WANPV = NPV - E[L_w] - C_a$$

where $WANPV$ is water-adjusted net present value, $E[L_w]$ is expected discounted water-related loss under scenario analysis, and C_a is adaptation capital and operating cost.

The purpose is not to produce a false single probability for drought or flood. Firms can calculate a range across plausible scenarios. If a project is profitable only when water risk is ignored, the investment case is weak.

Chapter 28

Water Security and National Economic Strategy

The national equivalent of water-adjusted capital allocation is to treat water as enabling infrastructure for growth. Industrial policy, food strategy, power planning, housing and data-centre policy should all include basin-level water constraints before incentives are granted.

A government that subsidises water-intensive industry in a stressed basin while separately financing emergency water supply is creating a fiscal contradiction. Integrated planning reduces this risk.

Part VII. Regional Water-Economic Security Profiles

Chapter 29

Middle East and North Africa: Structural Scarcity and Engineered Supply

29.1 The regional risk model

The Middle East and North Africa illustrate the difference between low natural water endowment and low water security. Several economies in the region face structural aridity, limited renewable freshwater, high population concentration in cities and substantial dependence on imported food. Yet some have built comparatively resilient municipal systems through desalination, storage, energy infrastructure, network investment and long-term planning. The economic-security challenge is therefore not scarcity alone. It is the cost, energy intensity and concentration of engineered supply, combined with groundwater depletion and agricultural pressure.

Desalination has altered the feasible frontier for coastal cities. It converts seawater into a relatively dependable source, but the resulting security depends on electricity, intake infrastructure, membranes, chemicals, distribution networks and marine-environment management. A disruption in power or coastal infrastructure can therefore become a water shock. The region demonstrates a general principle used throughout this paper: diversification improves resilience only when the new source does not reproduce the same dependency through another system. (World Bank, 2025b)

Food imports also function as a water-security instrument. By importing cereals, livestock feed and other water-intensive products, arid economies effectively import the water embedded in production. Virtual-water trade therefore reduces pressure on domestic resources, although it increases exposure to global food prices, exporting-country drought and trade restrictions. ('Trends and Environmental Impacts of Virtual Water Trade', 2024)

29.2 Strategic priorities to 2040

The strongest regional strategy combines demand discipline with supply diversification. Priorities include reducing network leakage, pricing water in ways that preserve basic access while discouraging waste, expanding wastewater reuse, protecting strategic aquifers, improving agricultural water productivity, lowering the energy intensity of desalination and maintaining emergency storage. Renewable electricity paired with desalination can reduce fuel exposure, but planners still need firm power, storage and network redundancy.

For financial analysis, projects should be tested against the full water-energy nexus. A desalination plant with secure financing but unreliable electricity is not a secure water asset. A new industrial zone with abundant coastal supply but inadequate wastewater capacity is not a resilient industrial system. Regional water strategy is therefore an exercise in systems engineering as much as hydrology.

Chapter 30

South Asia: Groundwater, Agriculture and Urban Scale

30.1 The regional risk model

South Asia combines large populations, intensive irrigated agriculture, rapid urbanisation, groundwater dependence, monsoon variability and growing industrial demand. Water stress is therefore transmitted simultaneously through food systems, cities, energy and labour markets. FAO data show agriculture remains the dominant global water-withdrawal sector, and the regional importance of irrigation makes water productivity central to both rural incomes and food security. (Food and Agriculture Organization of the United Nations, 2026b, 2026a)

Groundwater provides a buffer against rainfall variability because farmers and cities can pump when surface supplies weaken. That flexibility is economically valuable, but it becomes a liability when withdrawals exceed recharge or when electricity subsidies weaken incentives to conserve. Depletion can remain partly invisible for years because production continues until wells deepen, pumping costs rise, water quality deteriorates or aquifers lose resilience.

Urban growth adds another layer. Large metropolitan areas require treatment plants, distribution networks, drainage, flood control and wastewater systems to expand at a pace that often exceeds institutional capacity. The result can be the coexistence of flood exposure and water shortage in the same city. This is not contradictory. Flooding reflects inadequate drainage and extreme precipitation, while shortage can reflect depleted groundwater, polluted surface water, distribution losses or seasonal mismatch.

30.2 Strategic priorities to 2040

Priority measures include groundwater measurement, crop and irrigation reform, urban leakage reduction, wastewater treatment and reuse, aquifer recharge, flood-resilient drainage and stronger basin-level allocation. Agricultural policy matters because water demand is shaped by procurement rules, crop incentives, electricity pricing and land tenure as much as by irrigation hardware.

A South Asian water-security framework should also measure household time costs, informal water markets and service inequality. National averages can conceal large differences between neighbourhoods and between formal and informal settlements. WASH access therefore belongs inside macroeconomic and urban-productivity analysis rather than solely inside social-sector reporting. (WHO and UNICEF, 2025; World Health Organization, 2026)

Chapter 31

East Asia and Advanced Manufacturing: Water Quality as Industrial Infrastructure

31.1 The regional risk model

East Asia demonstrates how water security changes as economies become more technologically sophisticated. High-value manufacturing, semiconductor fabrication, chemicals, electronics and advanced materials often require water with strict quality specifications. The risk is therefore not only whether water exists, but whether sufficient volumes can be treated and delivered at the required purity and reliability.

Semiconductor production is a useful example. Fabrication facilities depend on ultra-pure water and tightly controlled process systems. Drought therefore poses an industrial risk even where total regional withdrawals appear manageable. Company investments in recycling, reclamation and site-level conservation demonstrate that water productivity is becoming part of manufacturing resilience. (Intel Corporation, 2026; Taiwan Semiconductor Manufacturing Company, 2026)

The strategic consequence is important. Industrial policy that seeks to localise advanced manufacturing without incorporating basin capacity, water quality, competing municipal demand and climate volatility can create hidden constraints. The same applies to battery plants, chemical facilities and large data-centre campuses.

31.2 Strategic priorities to 2040

Advanced manufacturing clusters should be planned through combined water, power, land and logistics assessments. Reclaimed water can reduce competition with municipal supplies. Industrial parks can also create shared treatment systems that improve economics compared with isolated facilities. Site-selection models should include drought frequency, source diversity, discharge constraints, utility governance and emergency continuity.

For governments competing for strategic investment, reliable water can become a location advantage. Yet subsidies designed to attract industry should not conceal the opportunity cost of water. Transparent allocation and cumulative-impact assessment are necessary where multiple large users enter the same basin.

Chapter 32

Europe: Drought, Flood, Rivers and Infrastructure Ageing

32.1 The regional risk model

Europe combines generally high infrastructure coverage with rising exposure to drought, heat, flood and river-flow variability. Mature networks reduce some service risks, but ageing infrastructure, ecological stress and climate extremes create a different challenge from basic-access deficits.

River systems are economically important for navigation, cooling, ecosystems and municipal supply. Low river levels can constrain shipping and industrial logistics. High water temperatures and low flows can also affect thermal power operations where cooling requirements and environmental discharge limits interact. In parallel, intense rainfall creates flood losses even in regions with sophisticated infrastructure.

The policy problem therefore involves adaptation of legacy systems designed around historical hydrological patterns. WMO's evidence of increasingly abnormal river-flow conditions reinforces the need to move beyond planning assumptions based only on historical averages. (World Meteorological Organization, 2026)

32.2 Strategic priorities to 2040

Europe's agenda includes floodplain restoration, urban drainage, river-basin coordination, infrastructure renewal, drought planning, agricultural adaptation and stronger integration of water into energy and industrial policy. Nature-based measures can complement engineered infrastructure by improving retention, reducing flood peaks and supporting ecosystems, although performance should be measured rather than assumed. (United Nations Environment Programme, 2024)

Financial institutions also have a larger role. Mature mortgage, insurance and corporate-credit systems transmit flood and drought risk into asset values, premiums and borrowing costs. OECD work on water-related financial stability makes this connection increasingly explicit. (OECD, 2025)

Chapter 33

Sub-Saharan Africa: Access, Infrastructure and Climate Volatility

33.1 The regional risk model

Across much of Sub-Saharan Africa, water-economic security is shaped by the interaction of basic-service gaps, rapidly growing cities, agricultural dependence, hydrological variability and constrained public finance. The challenge is therefore broader than physical scarcity. In many places, water exists but storage, treatment, distribution, sanitation or institutional capacity is insufficient to provide reliable services.

The economic consequences are direct. Time spent collecting water reduces labour and education opportunities. Unsafe water and sanitation increase disease burdens. Unreliable urban supply raises costs for households and firms, which may purchase from vendors, install storage or rely on private boreholes. These coping systems provide resilience at household level but can deepen inequality and weaken utility revenue.

WHO and UNICEF data show the global WASH deficit remains measured in billions of people, with the largest access gaps concentrated in lower-income settings. (WHO and UNICEF, 2025; World Health Organization, 2026) OECD and Global Commission estimates also indicate that economic losses from underinvestment in water security are disproportionately large in low-income economies. (Global Commission on the Economics of Water, 2024; OECD, 2026)

33.2 Strategic priorities to 2040

The priority sequence differs from high-income economies. Expanding safe basic access, improving utility governance, reducing non-revenue water, building fit-for-purpose storage, protecting watersheds and expanding sanitation often deliver higher social returns than frontier technologies. Digital monitoring has value, but it should support, not replace, core infrastructure and institutional capability.

Financing structures need to account for affordability. Full cost recovery through tariffs alone is unrealistic where incomes are low and network expansion needs are large. Blended public finance, targeted subsidies, concessional capital and stronger utility governance therefore belong in the investment model.

Chapter 34

The Americas: Abundance, Regional Scarcity and Infrastructure Chokepoints

34.1 The regional risk model

The Americas contain some of the world's largest freshwater systems, yet continental abundance does not eliminate local scarcity. Water security varies across arid western regions, tropical basins, agricultural zones, major cities, mining districts and small island states. Economic exposure therefore depends on location and infrastructure rather than national totals.

The Panama Canal provides the clearest illustration of water as globally significant trade infrastructure. Lock operations depend on freshwater stored in the watershed. During the 2023 to 2024 drought, draft and transit restrictions reduced capacity and altered shipping patterns. The event demonstrated how a hydrological shock in a relatively small geographic area can influence global logistics. (International Monetary Fund, 2025; Kamali et al., 2024; Panama Canal Authority, 2026)

Across the region, agriculture, mining and cities compete for water in specific basins. Hydropower also creates exposure to drought where electricity systems are highly dependent on reservoir inflows. Water-rich countries therefore still need source diversity, storage, drought protocols and environmental safeguards.

34.2 Strategic priorities to 2040

Priorities include basin-level planning, watershed protection, urban leakage reduction, drought-contingency rules, infrastructure maintenance and transparent allocation among agriculture, cities, ecosystems and industry. Where hydropower concentration is high, electricity planning should incorporate hydrological stress tests and generation diversity.

The Americas also offer opportunities for freshwater ecosystem conservation and green-water protection. Economic strategy should therefore value watershed services before degradation forces higher treatment, flood-control or supply costs.

Chapter 35

Small Island Developing States: Limited Storage and High Infrastructure Dependence

35.1 The regional risk model

Small island economies face a distinctive combination of limited land, small aquifers, rainfall variability, cyclone exposure, saline intrusion, high energy costs and dependence on imported equipment. Their water systems often have little redundancy. A single damaged treatment plant, contaminated aquifer or prolonged drought can therefore produce economy-wide effects.

Tourism can amplify seasonal demand precisely when local resources are stressed. Desalination offers a dependable source for many islands, but dependence on imported fuel or electricity can transfer water risk into energy risk. Wastewater reuse, rainwater harvesting and storage therefore become important complements.

Climate change introduces additional pressures through sea-level rise, storm damage and changing rainfall patterns. For low-lying islands, aquifer salinisation is a long-term strategic issue as well as an environmental concern.

35.2 Strategic priorities to 2040

Resilience requires distributed storage, emergency power, modular treatment, leak reduction, protected groundwater, rainwater capture, reuse and spare-parts planning. Infrastructure standards should reflect cyclone and flood exposure. Tourism policy should also include water-efficiency standards and transparent accounting of peak demand.

Small islands illustrate the weak-link principle particularly clearly. Their national water security can depend on a limited number of assets. Redundancy and rapid recovery therefore matter more than system size.

Chapter 36

Comparative Regional Synthesis

The regional profiles show why a single global water-security ranking is insufficient. The dominant constraint differs by economic structure and hydrology.

Region	Dominant exposure	Typical transmission channel	Priority resilience response
Middle East and North Africa	Structural scarcity and engineered-supply dependence	Energy cost, food imports, groundwater depletion	Diversified supply, reuse, demand discipline, strategic storage
South Asia	Groundwater, irrigation and urban scale	Food prices, farm income, urban service stress	Groundwater governance, irrigation reform, urban networks
East Asia	High-quality industrial water	Manufacturing continuity and cluster concentration	Recycling, reuse, source diversity, industrial water planning
Europe	Drought, flood and legacy infrastructure	Navigation, energy, insurance, asset damage	Adaptation, river-basin planning, infrastructure renewal
Sub-Saharan Africa	Basic access and infrastructure deficit	Health, labour, education, firm costs	WASH expansion, utility reform, storage and finance
Americas	Local scarcity within broad abundance	Trade routes, agriculture, hydropower, mining	Basin planning, drought protocols, source diversity
Small islands	Limited storage and asset concentration	Tourism, public health, energy dependence	Redundancy, modular supply, reuse, emergency systems

The comparison supports three conclusions. First, water endowment is an incomplete measure of resilience. Second, infrastructure and institutions often determine whether physical scarcity becomes economic disruption. Third, the optimal response portfolio changes by place. Global frameworks are useful only when translated into basin-specific and sector-specific decisions.

Part VIII. Quantitative Dashboard and Comparative Metrics

Chapter 37

A Global Water-Economic Security Dashboard

A research-grade monitoring system should distinguish observed hydrology, service conditions, economic dependence and adaptive capacity. Aggregating these dimensions too early can hide the reason risk is changing. The recommended dashboard therefore preserves separate indicators before constructing any composite score.

37.1 Core global observations

Indicator	Latest evidence used in this paper	Interpretation
River discharge	2025 among the driest years globally in a 35-year record	Short-run hydrological stress is elevated (World Meteorological Organization, 2026)
River-flow normality	Seven consecutive years with unusually low share of normal river flows	Historical averages are becoming less reliable for planning (World Meteorological Organization, 2026)
Safely managed drinking water	74% global coverage in 2024	Progress continues, but 2.1 billion people remain without safely managed service (WHO and UNICEF, 2025)
Safely managed sanitation	58% global coverage in 2024	Sanitation remains a larger service gap than drinking water (WHO and UNICEF, 2025)
Agriculture share of withdrawals	Approximately 69% in the harmonised FAO sector split used here	Food systems dominate direct withdrawals globally (Food and Agriculture Organization of the United Nations, 2026b)

Indicator	Latest evidence used in this paper	Interpretation
Countries at extremely high water stress	25 countries in WRI's Aqueduct assessment	Stress is geographically concentrated but economically important (Kuzma et al., 2023)
Population exposed to high stress at least one month per year	At least half of the world's population in WRI assessment	Seasonal risk is broader than annual national averages imply (Kuzma et al., 2023)
Economic loss from water underinvestment	OECD synthesis indicates around 8% of global GDP by 2050 under continued underinvestment, with larger losses in low-income economies	Water investment belongs in macroeconomic resilience analysis (OECD, 2026)
Data-centre electricity demand	About 415 TWh in 2024, rising toward more than 1,000 TWh by 2030 in IEA base case	Digital infrastructure is adding concentrated electricity and cooling demand (International Energy Agency, 2025b)

These indicators should not be combined mechanically. The global access figures describe households. Water-stress metrics describe pressure on renewable supply. River-discharge observations describe hydrological conditions. Economic-loss estimates are model outputs. Data-centre electricity demand is an infrastructure-demand measure. Each answers a different question.

Chapter 38

Sectoral Water-Criticality Matrix

The matrix below provides a qualitative research classification rather than an empirical ranking.

Sector	Quantity sensitivity	Quality sensitivity	Continuity sensitivity	Substitution potential	Geographic concentra-tion risk
Irrigated agriculture	High	Medium	High	Medium	Medium
Municipal water	High	High	Very high	Low	High locally
Semiconductors	Medium	Very high	Very high	Low in short run	High
Data centres	Medium locally	Medium	Very high	Medium through cooling design	High locally
Thermal power	High at site	Medium	High	Medium through technology mix	Medium
Hydropower	High	Low	High	Medium through grid diversity	High by basin
Mining and processing	Medium to high	Medium	High	Medium	High locally
Food processing	Medium	High	High	Medium	Medium
Tourism	Medium to high seasonally	High	High	Medium	High for islands and arid destinations
Inland navigation	High	Low	High	Medium through route substitution	High on specific rivers and canals

The purpose is to direct deeper measurement. A semiconductor cluster and an irrigated agricultural district can both be water exposed for entirely different reasons. The first depends heavily on quality and uninterrupted service. The second depends primarily on quantity, timing and land-water productivity. Policy should therefore address the mechanism rather than the label.

Chapter 39

A 2040 Strategic Outlook

The period to 2040 is likely to be shaped by five interacting forces.

First, climate volatility will increase the value of storage, forecasting and flexible allocation. WMO observations already show persistent abnormality in global river flows and declining land-water storage. (World Meteorological Organization, 2026)

Second, urbanisation will concentrate demand and economic value in metropolitan systems where a service failure produces large productivity losses. This raises the value of network maintenance, redundancy and wastewater reuse.

Third, industrial policy will create new water-intensive clusters. Semiconductor, battery, hydrogen, metals-processing and data-centre investments will increasingly require water-risk screening alongside electricity and land availability.

Fourth, financial markets will improve their spatial understanding of water exposure. Asset-level geolocation, basin data and physical-risk models are likely to make water risk more visible in credit, insurance and investment decisions. OECD work already points toward this integration. (OECD, 2025)

Fifth, governance quality will determine the economic outcome of physical scarcity. Regions that meter, allocate, price, maintain, reuse and cooperate effectively can support high-value economies under constrained natural supply. Regions with abundant water but weak infrastructure can remain insecure.

The strategic implication is not that every economy faces the same water crisis. It is that water is becoming a more material variable in economic planning across a wider set of sectors and geographies.

Part IX. Case Studies and System Lessons

Chapter 40

Panama Canal: Water as Trade Infrastructure

The Panama Canal demonstrates how local hydrology can affect global logistics. The canal depends on freshwater stored in Gatun and Alhajuela lakes for lock operations and also supports drinking-water supply for a large share of Panama's population. During the 2023-24 drought, daily transits were reduced and maximum draft limits tightened. The IMF reported that daily ship movements fell from normal levels of roughly 36-38 to 22-26 during part of the drought period. (International Monetary Fund, 2025)

The lesson is not that the canal is permanently unreliable. Operations recovered as rainfall returned. The strategic lesson is that the same resource supports domestic consumption and an international trade route. Water allocation therefore becomes part of trade resilience.

The 2026 Canal Authority updates show continued climate-management attention, including water-saving measures and draft adjustments as rainfall patterns changed. (Panama Canal Authority, 2026) This makes the canal a live example of adaptive operations rather than a one-time historical shock.

Chapter 41

Semiconductor Clusters: Ultra-Pure Water and Industrial Concentration

Semiconductor fabrication combines high capital intensity, geographic concentration and demanding water quality. Water shortages do not need to shut an entire country's water system to create global effects. A disruption at a small number of advanced fabs could affect supply chains far beyond the basin.

Intel and TSMC disclosures show substantial investment in conservation, reclaimed water and watershed programmes. (Intel Corporation, 2026; Taiwan Semiconductor Manufacturing Company, 2026) These actions should be interpreted as corporate resilience measures rather than proof that water risk has been eliminated.

The broader lesson is that strategic-industry policy should evaluate cumulative water demand across industrial clusters. Multiple projects that appear manageable individually can become material when combined.

Chapter 42

AI Data Centres: Planning for Cumulative Local Demand

Data centres illustrate a new type of water-planning challenge. Demand arrives in large increments, project schedules can be faster than utility expansion, and local water impact varies with technology. The IEA's electricity outlook suggests rapid growth in the sector through 2030. (International Energy Agency, 2025b, 2026)

Water permitting should therefore be integrated with power-grid planning and land-use approvals. Recycled water, direct-to-chip cooling, air cooling and closed-loop systems expand the design space. The risk is highest when multiple facilities cluster in a stressed region and rely on the same utility or watershed.

Chapter 43

Urban Reuse: Turning Wastewater into Supply

The World Bank's 2025 reuse work argues that treated wastewater becomes economically attractive where supply and demand are spatially close, particularly in cities and industrial parks. (World Bank, 2025c) Reuse provides two benefits at once. It reduces pollution discharge and adds a drought-resilient source.

The key lesson is institutional. Reuse requires quality standards, pricing, separate distribution where needed, long-term off-take and public confidence. Technology alone does not produce a viable market.

Chapter 44

Water and Power: Drought as an Energy-Security Shock

Recent hydropower variability demonstrates the connection between rainfall and electricity security. The IEA reported drought-related hydro constraints in 2023 and 2025 across multiple regions. (International Energy Agency, 2025a) Thermal power plants have also faced water-related limits during heat and drought. (International Energy Agency, 2023)

The lesson is to include hydrological scenarios in power-system adequacy. A power system with high hydro dependence should evaluate multi-year drought. A thermal-heavy system should evaluate cooling-water constraints during heatwaves. Water and electricity planning should not use separate climate assumptions.

Chapter 45

WASH Systems: Security Begins with Basic Services

The most sophisticated water-security strategy fails if households lack safe water and sanitation. The global access gaps documented by WHO and UNICEF remain a reminder that water security is not only about strategic industry. (WHO and UNICEF, 2025)

The economic lesson is that investment in WASH has broad returns through health, time and human capital. OECD's 2026 report cites an approximate four-to-one benefit ratio for water and sanitation investment, though returns vary by project and context. (OECD, 2026)

Part X. Scenarios to 2040

Chapter 46

Scenario Method

Scenarios in this paper are structured stress tests. They do not assign probabilities or claim that one future will occur. Each scenario changes a small number of system variables and asks how effects transmit through food, energy, industry, cities, trade and finance.

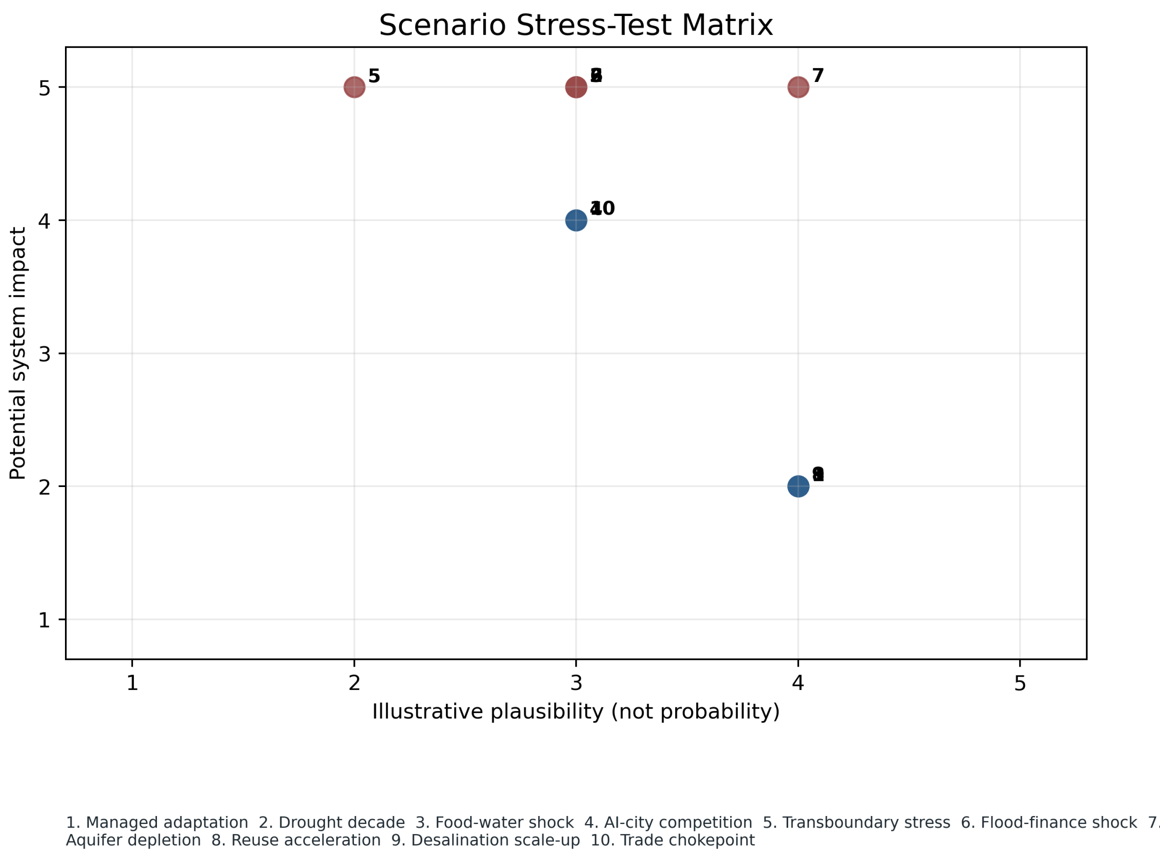

Figure 46.1: Illustrative scenario stress-test matrix.

Chapter 47

Twenty Core Scenarios

47.1 Scenario 1: Managed adaptation

Hydrological volatility rises gradually, but investment in leakage reduction, reuse, storage, watershed protection and drought planning keeps service reliability broadly stable. Water becomes a routine capital-allocation variable rather than a crisis issue. Economic losses are contained, though tariffs and public investment rise.

47.2 Scenario 2: The drought decade

Several major agricultural and hydropower regions experience repeated multi-year drought. Food inventories fall, hydro output weakens and groundwater pumping accelerates. Countries with diversified food imports and power systems outperform those dependent on one climatic region.

47.3 Scenario 3: Global food-water shock

Drought affects multiple grain exporters in the same season. Export restrictions amplify price increases. Import-dependent low-income countries face balance-of-payments and food-security stress. Strategic grain reserves and diversified procurement become temporary stabilisers.

47.4 Scenario 4: AI-city water competition

Rapid data-centre clustering occurs in several water-stressed metropolitan regions. Public opposition rises after drought restrictions affect households. New permits require reclaimed water, closed-loop cooling and drought curtailment plans. Data-centre growth shifts toward regions with stronger water and power portfolios.

47.5 Scenario 5: Transboundary drought escalation

A shared river basin experiences several years of low flow. Upstream infrastructure and agricultural withdrawals become politically contested. Countries with functioning joint institutions preserve data exchange and negotiated allocation. Weakly governed basins face higher diplomatic and domestic stress.

47.6 Scenario 6: Flood-finance shock

A sequence of severe floods affects major urban property markets. Insurance availability falls and mortgage collateral is repriced. Public reconstruction costs rise while property tax bases weaken. Financial supervisors begin requiring basin and flood-zone stress tests.

47.7 Scenario 7: Aquifer depletion becomes visible

Groundwater levels fall below economically viable pumping depths across a major farming region. Land subsidence damages infrastructure. Agricultural land values fall and rural credit deteriorates. Governments face pressure to cap withdrawals and fund transition support.

47.8 Scenario 8: Water reuse acceleration

Cities adopt large-scale municipal and industrial reuse. Wastewater becomes a contracted resource. Industrial parks co-locate treatment and reuse systems. Freshwater withdrawals decline for non-potable uses, while regulation and public acceptance mature.

47.9 Scenario 9: Desalination scale-up

Lower-cost renewable power and improved membranes accelerate desalination in coastal water-stressed regions. Brine regulation tightens. Inland regions benefit less because transport and disposal remain costly.

47.10 Scenario 10: Shipping chokepoint drought

A major canal or river corridor faces low water during a period of geopolitical disruption elsewhere. Freight rates rise sharply because alternative routes are already constrained. Inventory and route diversification become more valuable than in isolated water shocks.

47.11 Scenario 11: Water-quality crisis

A major industrial basin experiences widespread contamination. Quantity remains adequate, but treatment capacity becomes the binding constraint. Production falls because process-water quality specifications cannot be met. Liability and remediation costs increase.

47.12 Scenario 12: Groundwater regulation shock

Authorities impose rapid pumping restrictions after evidence of depletion. Agricultural and industrial users with no alternative source face stranded capital. Firms that invested earlier in recycling and diversified sourcing gain relative advantage.

47.13 Scenario 13: Nature-restoration dividend

Watershed restoration, wetland recovery and soil programmes improve base flows and reduce flood peaks in several regions. Benefits accrue slowly but reduce engineered-infrastructure requirements and improve biodiversity. Finance models evolve to monetise avoided losses.

47.14 Scenario 14: Pricing reform backlash

Governments raise water tariffs to fund infrastructure without adequate protection for low-income households or transparent service improvements. Public resistance stalls reform. The case shows that pricing is an institutional and distributional policy, not only an efficiency instrument.

47.15 Scenario 15: Financial repricing

Banks and insurers receive better basin-level exposure data. Water-sensitive assets face higher capital and insurance costs in stressed regions. Investment shifts toward resilient facilities and regions. Poor disclosure becomes a financing disadvantage.

47.16 Scenario 16: Industrial relocation

A manufacturing cluster experiences repeated restrictions. New plants locate elsewhere despite higher labour or logistics costs because water reliability dominates marginal cost differences. Existing sunk assets invest in reuse rather than relocate.

47.17 Scenario 17: Climate migration from water stress

Persistent agricultural water decline reduces rural incomes and accelerates migration to cities. Urban water, housing and labour markets face pressure. The core policy challenge becomes coordinated rural adaptation and urban service expansion.

47.18 Scenario 18: Virtual-water realignment

Countries begin evaluating the water risk embedded in food imports. Procurement shifts toward suppliers with stronger hydrological resilience. Trade patterns change even without tariffs.

47.19 Scenario 19: Insurance retreat

Repeated flood and drought losses make insurance unaffordable or unavailable in selected regions. Governments become insurers of last resort. Land-use policy and public adaptation investment become fiscal-risk tools.

47.20 Scenario 20: Water-data revolution

Satellite monitoring, smart metering and open data sharply improve measurement. Illegal abstraction and leakage become more visible. Better data initially increases reported risk because hidden problems are revealed, then supports more efficient investment.

Chapter 48

Compound Shock Scenarios

48.1 Compound A: Drought plus food export controls

Production falls in multiple exporting regions and governments restrict exports to protect domestic prices. Importers face both physical scarcity and policy-induced supply reduction. The shock tests trade agreements, reserves, foreign exchange and social protection.

48.2 Compound B: Heatwave plus hydro and thermal constraints

Extreme heat raises power demand while low water reduces hydro output and limits thermal cooling. Electricity prices rise, affecting pumping and treatment. Water and power systems become mutually reinforcing constraints.

48.3 Compound C: AI expansion plus urban drought

A city attracts large data-centre investment before completing water and power upgrades. Drought triggers household restrictions. Public legitimacy deteriorates. Projects with reclaimed-water systems continue operating while others face curtailment.

48.4 Compound D: Flood plus sovereign debt stress

Severe flooding damages infrastructure in a highly indebted country. Reconstruction needs rise as borrowing costs increase. Deferred water and drainage maintenance creates a negative feedback loop.

48.5 Compound E: Trade chokepoint drought plus geopolitical route closure

Water constraints reduce capacity at one major route while conflict reduces capacity at another. Global shipping faces limited substitution. Commodity prices rise and just-in-time supply chains experience longer delays.

48.6 Compound F: Transboundary drought plus domestic political stress

Low flows coincide with elections, food-price pressure or internal conflict in one or more basin states. Negotiating space narrows. Existing treaties and technical commissions become especially valuable because they preserve communication during political stress.

Part XI. Strategic Implications

Chapter 49

Government Strategy

49.1 Put water inside economic planning

Water ministries and utilities rarely control the decisions that drive the largest changes in water demand. Agriculture ministries shape irrigation and crop incentives. Energy ministries influence hydropower, cooling and desalination. Industry agencies select zones and provide investment incentives. Local governments approve housing and data centres. Finance ministries decide public investment and subsidies. Environmental agencies protect watersheds and quality. Economic security therefore requires a cross-government water lens.

A practical test is to require major public and industrial strategies to state their water assumptions. An industrial policy should identify expected basin demand. A power plan should quantify hydrological exposure. A food strategy should show groundwater trends and virtual-water dependence. A housing plan should include water and drainage capacity. A data-centre strategy should evaluate cumulative local water and power demand.

49.2 Build a national water balance sheet

Traditional budgets record fiscal assets and liabilities but rarely record water-system condition in a comparable way. A national water balance sheet should track renewable supply, storage, groundwater change, infrastructure condition, WASH access, ecosystem status, utility finances and contingent disaster exposure.

This does not require assigning a single market value to all water. It requires making depletion and resilience visible. If aquifers are falling while GDP rises, the system is drawing down natural capital. If reservoirs are losing capacity through sedimentation, apparent storage is overstated. If utilities cannot fund maintenance, infrastructure liabilities are accumulating.

49.3 Classify strategic water uses

Governments need an allocation hierarchy before drought. Basic human needs, public health and critical services require protection. Environmental flows maintain the resource base. Food and strategic industry require rules that balance economic value with social and ecological costs.

Drought allocation should be pre-agreed where possible. Emergency decision-making is less credible when users do not know priorities or compensation rules.

49.4 Make water-risk disclosure decision useful

Reporting should focus on location and dependency rather than total corporate withdrawal alone. National regulation should ask large users to disclose basin, source, quality requirement, withdrawal and consumption, reuse, discharge, drought contingency and material supplier exposure.

The objective is not reporting volume for its own sake. It is to make cumulative demand and system vulnerabilities visible to planners, investors and communities.

Chapter 50

Corporate Strategy and Board Oversight

50.1 Water belongs in enterprise risk management

Boards should treat water as an operational and strategic variable where exposure is material. The first step is not setting a public target. It is mapping dependency.

A complete map should identify direct facility use, utility reliance, groundwater and surface sources, process-quality requirements, wastewater constraints, upstream supplier exposure, downstream customer dependence and local community competition. The analysis should then estimate the effect of drought, flood, contamination, tariff change, permit tightening and service interruption.

50.2 Move beyond litres per unit of output

Water-intensity metrics are useful but incomplete. A low-intensity operation in an extremely stressed basin may carry more risk than a high-intensity operation in a water-abundant basin. A company can improve global efficiency while increasing exposure if production shifts into more stressed locations.

Board dashboards should therefore combine intensity with basin stress, source concentration, recycling rate, storage days, business-continuity time and supplier exposure.

50.3 Treat water resilience as capital productivity

Reuse systems, storage, alternate intakes, cooling redesign and watershed investment should be evaluated against avoided downtime and licence-to-operate risk. The business case is stronger where interruption costs are high.

Water capex is often judged only against tariff savings. This understates value. A resilient water system can preserve production during drought, reduce permit risk and support future expansion.

50.4 Supplier due diligence

Tier-one suppliers can hide upstream water concentration. Semiconductor, chemical, agricultural and mining supply chains are especially exposed to location-specific risk. Procurement teams should ask whether multiple suppliers rely on the same basin, aquifer, port or utility.

Chapter 51

Financial Institutions and Investors

51.1 Map portfolios to basins

Sector classification is not enough. Two food processors may have very different exposure if one operates in a resilient basin and the other depends on depleted groundwater. Banks and investors should map material assets to basin-level indicators, then adjust for adaptation capacity.

51.2 Avoid mechanical exclusion

A water-stressed location is not automatically uninvestable. High stress can coexist with strong reuse, governance and diversified supply. Screening should distinguish exposure from vulnerability.

51.3 Stress testing

A financial water stress test should include at least four shock types: chronic scarcity, acute drought, severe flood and regulatory transition. Loss channels include production, input costs, collateral damage, insurance changes, capex, asset life and sovereign support.

OECD work notes that water-risk methods are still developing. (OECD, 2025) This supports a scenario approach rather than false precision.

Chapter 52

Universities and Research Institutions

52.1 A research agenda beyond the water sector

Water research increasingly requires economists, hydrologists, engineers, public-health specialists, agronomists, climate scientists, political scientists, finance researchers and data scientists. The strongest studies connect physical variables to economic outcomes without treating one discipline's model as complete.

Research priorities include basin-level firm exposure, groundwater accounting, water and inflation, water-related credit losses, virtual-water concentration, data-centre water intensity, industrial relocation, adaptation returns and distributional effects of pricing.

52.2 Open science and reproducibility

Researchers should publish basin definitions, data vintages, missing-data treatment, scenario assumptions and code where licensing permits. Water datasets often combine observations and models. Reproducibility requires clarity about which is which.

Chapter 53

Development Strategy for Emerging Economies

53.1 Avoid importing high-income infrastructure models blindly

Water systems should match fiscal capacity, climate, settlement patterns and operating capability. Capital-intensive infrastructure that cannot be maintained can reduce resilience. Decentralised treatment, managed aquifer recharge, small storage, nature-based solutions and targeted reuse may outperform large projects in some settings.

53.2 Water as a competitiveness asset

Reliable water can support manufacturing, tourism, agriculture and digital infrastructure. Emerging economies seeking new investment should treat water reliability as part of industrial competitiveness, alongside electricity, ports and workforce.

The objective should be resilience without sacrificing access for households or ecosystems. Industrial incentives that socialise water costs can create long-term conflict and fiscal burden.

Part XII. Early Warning Architecture

Chapter 54

Forty-Eight Indicators for a Water-Economic Security Dashboard

The dashboard below is designed as a monitoring architecture rather than a universal scoring system. Indicator thresholds should be calibrated locally.

54.1 Hydrology and source condition

1. Twelve-month precipitation percentile relative to local history.
2. River discharge percentile at critical gauges.
3. Reservoir storage as a share of seasonal target.
4. Groundwater-level trend at strategic aquifers.
5. Soil-moisture anomaly in major agricultural regions.
6. Glacier or snow-water-equivalent trend where relevant.

54.2 Water demand and allocation

7. Total withdrawals by sector.
8. Consumptive use by sector where measurable.
9. Peak-season demand relative to reliable yield.
10. Share of withdrawals from groundwater.
11. Number and duration of emergency restrictions.
12. Unauthorised or unmetered abstraction estimate.

54.3 Urban and WASH systems

13. Safely managed drinking-water coverage.
14. Safely managed sanitation coverage.
15. Non-revenue water.
16. Average daily storage in major urban systems.
17. Treatment-plant capacity utilisation.
18. Household water expenditure for the lowest income quintile.

54.4 Agriculture and food

19. Irrigation withdrawals per unit of crop value.
20. Share of irrigated area dependent on declining aquifers.
21. Crop-water productivity for major crops.

22. Drought insurance coverage.
23. Food-import concentration weighted by supplier water stress.
24. Strategic food inventory days.

54.5 Industry, energy and technology

25. Water withdrawal and consumption of strategic industrial clusters.
26. Recycled-water share for major industrial users.
27. Number of critical facilities dependent on one source.
28. Hydropower generation deviation from expected seasonal output.
29. Thermal-generation capacity exposed to cooling-water restrictions.
30. Data-centre water demand relative to local utility capacity.

54.6 Ecosystems and water quality

31. Environmental-flow compliance.
32. Wetland area and condition.
33. Number of water-quality exceedances at major intakes.
34. Nutrient concentrations in strategic lakes and rivers.
35. Salinity trend in coastal aquifers and deltas.
36. Wastewater treatment and reuse rate.

54.7 Finance and infrastructure

37. Utility operating-cost recovery ratio.
38. Water infrastructure maintenance backlog.
39. Annual water-security investment as a share of public capital spending.
40. Insured versus uninsured flood losses.
41. Bank exposure to water-sensitive sectors in stressed basins.
42. Cost of capital for utilities and water projects.

54.8 Governance and transboundary cooperation

43. Share of major users metered and permitted.
44. Time required to resolve allocation disputes.
45. Publication lag for hydrological data.
46. Share of transboundary waters covered by operational agreements.
47. Frequency of joint drought and flood exercises.
48. Compliance with agreed transboundary data exchange.

Chapter 55

Indicator Interpretation

No single indicator should trigger a crisis label. Water systems fail through combinations. Falling reservoir levels are more serious when groundwater is also declining and urban leakage is high. A flood forecast is more dangerous when drainage maintenance is weak and insurance penetration is low. The dashboard therefore needs correlation and escalation rules.

A practical traffic-light system should require two conditions for escalation: a physical threshold and a vulnerability threshold. For example, low river flow plus high hydropower dependence would generate a stronger warning than low flow in a diversified power system.

Part XIII. Research Hypotheses

Chapter 56

Eighteen Testable Hypotheses

56.1 H1. Weak-link hypothesis

National economic loss from water shocks is better predicted by the weakest domain in the Water Security Systems Framework than by average national water availability.

56.2 H2. Source-diversity hypothesis

Cities with more independent water sources experience shorter and less severe rationing during drought after controlling for income and climate.

56.3 H3. Utility-finance hypothesis

Utility cost recovery and maintenance expenditure predict service continuity more strongly than headline capital spending.

56.4 H4. Groundwater-liability hypothesis

Regions with persistent groundwater decline experience higher long-run agricultural credit risk and land-value volatility.

56.5 H5. Virtual-water diversification hypothesis

Food-import portfolios diversified across hydrologically uncorrelated suppliers experience lower price volatility during drought shocks.

56.6 H6. Industrial-concentration hypothesis

Water shocks in highly concentrated industrial clusters generate larger global supply-chain effects than shocks of similar hydrological severity in diversified production networks.

56.7 H7. Reuse-resilience hypothesis

Industrial facilities with high recycled-water shares experience fewer drought-related production losses after controlling for sector and basin stress.

56.8 H8. Data-quality hypothesis

Basins with real-time public monitoring and metering resolve drought allocation earlier and with lower economic loss than basins with weak information systems.

56.9 H9. Transboundary-institution hypothesis

Shared basins with operational joint institutions experience fewer crisis-era unilateral allocation measures than comparable basins without such institutions.

56.10 H10. Water-finance hypothesis

Bank portfolios with high geographic concentration in water-stressed basins show higher credit deterioration after drought than sectorally similar but geographically diversified portfolios.

56.11 H11. Flood-insurance hypothesis

Insurance retreat occurs first where repeated flood loss, weak adaptation and rising reconstruction cost coincide, rather than where hazard alone is highest.

56.12 H12. Pricing-legitimacy hypothesis

Tariff reform produces more durable conservation when revenue is visibly linked to service improvement and low-income protection.

56.13 H13. Rebound hypothesis

Irrigation-efficiency gains do not reduce basin withdrawals where irrigated area or crop intensity expands without enforceable allocation limits.

56.14 H14. Data-centre siting hypothesis

Water constraints increasingly influence data-centre location at the margin after electricity and fibre requirements are satisfied.

56.15 H15. Ecosystem-buffer hypothesis

Watershed condition predicts lower flood and drought loss after controlling for engineered infrastructure and income.

56.16 H16. Water-adjusted capital hypothesis

Projects evaluated with water-adjusted cash-flow scenarios experience fewer unplanned water capex requirements than projects using conventional NPV alone.

56.17 H17. Compound-risk hypothesis

Economic losses from simultaneous water and energy shocks exceed the sum of losses from isolated shocks because of network feedbacks.

56.18 H18. Transparency-cost-of-capital hypothesis

Firms with credible basin-level water disclosure and adaptation plans face lower financing penalties in stressed regions than peers with similar physical exposure but poor disclosure.

Chapter 57

Proposed Empirical Methods

The hypotheses invite several methods. Panel-data models can connect hydrology to output and credit. Event studies can measure market response to water restrictions. Difference-in-differences designs can test reuse and pricing reforms. Survival analysis can measure project interruption. Input-output models can estimate supply-chain propagation. Network models can identify basin and supplier concentration. System-dynamics models can test feedbacks across water, power and food.

Researchers should pre-register key definitions where feasible because water studies are sensitive to basin boundaries, drought metrics and exposure windows.

Part XIV. Executive and Academic Q&A

Chapter 58

Fifty Questions and Answers

58.1 1. Is the world running out of water?

Not in a simple global volumetric sense. Water circulates through the hydrological cycle. The problem is that usable water is unevenly distributed across place and time, quality is degraded in many systems, groundwater and storage are being depleted in some regions, and climate change is altering variability. The security problem is reliable access to the right quality at the right time.

58.2 2. What is the difference between water scarcity and water security?

Scarcity describes insufficiency relative to demand or access. Security is broader. It includes reliability, quality, affordability, infrastructure, ecosystem health, institutions and the ability to absorb shocks. A water-scarce country can be secure with strong management, while a water-rich country can experience severe service failure.

58.3 3. Why should finance ministries care about water?

Water affects growth, inflation, public investment, disaster costs, utility subsidies, food imports and tax revenue. OECD now treats water-related risk as relevant to financial stability. (OECD, 2025) Water shocks can move from environmental systems into sovereign and private balance sheets.

58.4 4. Is agriculture still the main global water user?

Yes. FAO's global aggregate attributes about 69 percent of withdrawals to agriculture, with higher shares in many developing regions. (Food and Agriculture Organization of the United Nations, 2026b) The share varies widely by geography and should not be confused with consumption.

58.5 5. Does improving irrigation efficiency always save water?

No. Efficiency lowers water use per unit of production, but total basin withdrawals can stay flat or rise if farmers expand irrigated area or shift to more water-intensive crops. Efficiency is strongest when paired with allocation rules and monitoring.

58.6 6. What is virtual water?

Virtual water is the water embodied in producing traded goods. Research estimates that roughly 20 percent of water used in global food production is associated with internationally traded products. ('Trends and Environmental Impacts of Virtual Water Trade', 2024) This makes trade part of global water allocation.

58.7 7. Are water wars inevitable?

No. Water stress can intensify tensions, but shared water also creates incentives for cooperation. Institutions, treaties, data exchange and wider political relationships shape outcomes. Deterministic claims about inevitable wars are not supported by the complexity of observed cooperation.

58.8 8. Why are transboundary agreements important?

They establish rules before crisis. Shared basins need procedures for data, allocation, pollution, floods and droughts. UNECE and UNESCO report that 153 countries depend on transboundary waters, while only a minority have effective arrangements covering most shared waters. (UNECE and UNESCO, 2024)

58.9 9. Is desalination the solution to global water scarcity?

It is one important option, especially for coastal arid regions. It is not a universal solution. Desalination requires capital, electricity and brine management, and inland transport raises cost. Governance, efficiency and reuse remain necessary.

58.10 10. Is wastewater reuse safe?

Reuse is safe when treatment and monitoring match the intended use. Standards differ for industrial cooling, agriculture, indirect potable reuse and direct potable reuse. The key is fit-for-purpose treatment, regulatory control and transparent quality assurance.

58.11 11. Why is groundwater difficult to manage?

It is less visible than surface water, often privately pumped, and monitoring wells are incomplete. Depletion can continue for years before economic consequences become obvious. Groundwater also crosses property and political boundaries.

58.12 12. How does water affect electricity security?

Hydropower depends on flows and reservoir levels. Thermal plants often need cooling water. Water treatment and pumping need electricity. Drought and heat can stress both systems at once.

58.13 13. Does renewable energy reduce water risk?

Solar PV and wind generally have low operational water requirements compared with many thermal technologies, which can reduce water dependence in power generation. Hydropower remains directly hydrology dependent. Manufacturing and mining inputs also carry water footprints.

58.14 14. Why are semiconductors water sensitive?

Fabrication requires large amounts of highly purified water for process steps and cleaning. The critical issue is not only volume but purity and reliability. A supply interruption can stop high-value production.

58.15 15. Are AI data centres a major global water threat?

Agriculture remains far larger globally. The data-centre issue is local concentration. Large facilities can create material demand in particular utilities or basins, especially where evaporative cooling and water-intensive electricity generation are used.

58.16 16. What should regulators ask of data-centre projects?

They should ask about source, withdrawal and consumption, cooling design, recycled-water potential, drought operations, electricity mix, cumulative local demand and public reporting. The same standard should apply to other large water users.

58.17 17. What is the best single water-security metric?

There is no adequate single metric. Stress ratios, access, groundwater trends, quality, storage and governance measure different dimensions. Composite indices are useful for screening but need local validation.

58.18 18. Why use a geometric mean in the proposed WSRI?

Because water security has weak-link properties. An arithmetic average can hide a critical failure in one domain. The geometric mean gives greater penalty to very low scores while still rewarding balanced improvement.

58.19 19. Has the proposed WSRI been validated?

No. It is an original research framework proposed in this paper. It requires empirical testing against observed losses, rationing, industrial interruptions and recovery performance before use as a ranking tool.

58.20 20. What is the Strategic Water Exposure Score?

It is a proposed facility or sector screening measure combining operational dependence, source stress, concentration and recovery difficulty. It identifies where water exposure is strategically material. It does not estimate expected financial loss.

58.21 21. How should companies value water resilience investments?

They should compare capex and operating cost against avoided downtime, permit risk, expansion constraints, emergency procurement and reputational loss. Tariff savings alone are too narrow.

58.22 22. Is water risk already priced by financial markets?

Only partially. Some insurers, lenders and investors use flood and drought data, but basin-level corporate exposure and adaptation capacity remain poorly standardised. OECD describes integration into financial supervision as developing rather than mature. (OECD, 2025)

58.23 23. What role does insurance play?

Insurance transfers some financial risk and creates price signals. It cannot solve chronic physical scarcity or substitute for land-use planning. In high-risk regions, premiums can become unaffordable or coverage can retreat.

58.24 24. How does water affect sovereign credit?

Severe water shocks can reduce output, raise food and power prices, increase public support needs and require reconstruction spending. Countries with weak fiscal buffers face larger secondary effects.

58.25 25. Why is water quality an economic-security issue?

Poor quality reduces effective supply. Treatment costs rise, industrial uses can be disrupted and public health deteriorates. Quantity-based assessments can therefore overstate usable water.

58.26 26. Does climate change always reduce rainfall?

No. Climate change alters intensity, timing and spatial distribution. Some regions become wetter, some drier, and extremes can increase in both directions. Water security is therefore about volatility as well as average supply.

58.27 27. What does WMO's 2025 water report add?

It provides a current global hydrological baseline. WMO reports that 2025 was among the driest river-discharge years in 35 years, with continued abnormal flows, terrestrial water-storage decline and glacier loss. (World Meteorological Organization, 2026)

58.28 28. Is one dry year enough to prove a long-term trend?

No. The strength of the WMO finding is not one year alone. It sits within multiple years of abnormal flow and longer-term storage and glacier trends. Local attribution still requires basin-specific analysis.

58.29 29. Why is ecosystem health part of economic security?

Wetlands, forests and soils store water, filter pollutants and reduce flood peaks. Their degradation increases demand for engineered treatment, storage and protection. Ecosystem loss therefore creates replacement costs and higher vulnerability.

58.30 30. Should water be priced at full economic value?

Pricing should encourage efficient use and fund reliable service, but basic access must remain affordable. Water also has ecological and social values not captured by market price. Pricing is one instrument within a broader rights and governance framework.

58.31 31. What is non-revenue water?

It is treated water that produces no billed revenue because of physical leaks, theft, metering errors or billing problems. High non-revenue water wastes source, treatment and energy capacity and weakens utility finances.

58.32 32. Is building more reservoirs enough?

No. Storage is useful, but reservoir performance depends on inflows, sedimentation, operations and environmental trade-offs. Groundwater, wetlands, soil moisture, reuse and demand management are also forms of resilience.

58.33 33. What is green water?

Green water is water stored in soil and vegetation that supports plants and ecosystems. It is central to rainfed agriculture and land-climate interactions. Recent planetary-boundary research treats green-water change as a core component of freshwater-system risk. (Richardson et al., 2023; Wang-Erlandsson et al., 2022)

58.34 34. Why should trade ministries care about water?

Water affects shipping routes and the reliability of imported goods. The Panama Canal drought showed direct logistics exposure, while virtual-water trade creates indirect dependence on supplier hydrology. (International Monetary Fund, 2025; 'Trends and Environmental Impacts of Virtual Water Trade', 2024)

58.35 35. What was the Panama Canal lesson?

A local freshwater shortage constrained a route handling around 5 percent of global maritime trade. (Kamali et al., 2024) The same reservoirs also support domestic water supply. The case shows how local allocation can have global spillovers.

58.36 36. Does water scarcity always reduce economic growth?

No. Outcomes depend on management, infrastructure, sector structure and adaptation. World Bank modelling found that policy improvements can sharply reduce projected losses. (World Bank, 2016)

58.37 37. What are the highest-return interventions?

There is no universal ranking. Leakage reduction can be high return in poorly maintained cities. Irrigation reform matters in agricultural basins. Reuse is attractive near large wastewater sources and industrial demand. Watershed restoration has long-term benefits. Desalination fits some coastal systems.

58.38 38. Why is data quality itself a resilience issue?

Allocation decisions are worse when withdrawals, groundwater or quality are unknown. Disputes intensify when users do not trust data. Monitoring reduces uncertainty and improves enforcement.

58.39 39. How should governments prioritise water investment?

They should compare projects on reliability gain, avoided loss, public-health benefit, lifecycle cost, distributional effect, climate performance and ecosystem impact. Project size should not be a proxy for value.

58.40 40. What should a corporate board ask management?

Which facilities and suppliers are in stressed basins? Which processes stop first if water is restricted? How many days of storage exist? What alternatives are qualified? What reuse options are economic? How does water affect planned expansion?

58.41 41. What should banks ask borrowers?

They should ask about location, source, dependence, permits, treatment, historical restrictions, adaptation capex and insurance. Generic ESG scores are less useful than asset-level information.

58.42 42. How should universities contribute?

Universities should connect hydrology with economics, finance, engineering, public health and political institutions. They should also improve open data, causal methods and reproducible basin-level research.

58.43 43. What is the biggest analytical mistake in water security?

Using national annual averages to judge local operational risk. Water problems are often seasonal and basin specific.

58.44 44. What is the biggest policy mistake?

Expanding supply without fixing incentives, maintenance and allocation. New capacity can be absorbed by rising demand while structural weaknesses remain.

58.45 45. What is the biggest corporate mistake?

Reporting total water use without identifying where use occurs and whether sources are stressed, concentrated or replaceable.

58.46 46. What is the biggest financial-sector mistake?

Treating water as a niche environmental issue rather than a potential driver of credit, market, operational and insurance risk in exposed portfolios.

58.47 47. What does resilience mean in practice?

Resilience means maintaining essential service and recovering quickly after shocks. It comes from redundancy, storage, diversified sources, efficient use, strong institutions, emergency protocols and finance.

58.48 48. Is self-sufficiency the goal?

No. Trade, shared infrastructure and transboundary cooperation often increase resilience. The goal is managed dependence with credible alternatives where failure would be costly.

58.49 49. What should change by 2030?

Countries should have better groundwater monitoring, stronger WASH systems, lower leakage, drought and flood plans, basin-level industrial screening, more reuse, transparent allocation and stronger cross-border cooperation. The exact mix differs by location.

58.50 50. What is the paper’s central conclusion?

Water security is economic security because water shocks move through food, energy, industry, cities, trade and finance. Resilience depends less on natural abundance alone than on the quality of the system built around the resource.

Part XV. Policy Toolkits

Chapter 59

Government Due-Diligence Checklist

Before approving a major water-sensitive policy or project, governments should ask:

1. Which basin, aquifer or utility serves the project?
2. What is reliable yield under drought conditions?
3. What is the latest groundwater trend?
4. What competing human and ecological demands exist?
5. What is the project's withdrawal and consumption profile?
6. What quality specification does it require?
7. What share can be met through reclaimed water?
8. What is the drought-curtailment plan?
9. Does the utility have sufficient treatment and network capacity?
10. What electricity demand is created by pumping or treatment?
11. What wastewater-discharge capacity is required?
12. What cumulative demand from other approved projects exists?
13. What flood exposure exists at the site and along logistics routes?
14. What source redundancy exists?
15. What storage is available?
16. Which permits or water rights are required?
17. Are allocation priorities defined during shortage?
18. What community consultation is required?
19. What ecosystem impacts arise?
20. What climate assumptions underpin design?
21. What monitoring data will be public?
22. What is the lifecycle maintenance plan?
23. Who bears emergency-supply cost?
24. What financing risks arise if tariffs change?
25. What review or sunset condition applies to water-intensive incentives?

Chapter 60

Corporate Water-Security Checklist

1. Map all material facilities to basins and aquifers.
2. Map major suppliers beyond Tier 1 where water exposure is material.
3. Separate withdrawal from consumption.
4. Track water quality requirements by process.
5. Measure source concentration.
6. Measure storage days.
7. Identify drought curtailment thresholds.
8. Identify flood shutdown thresholds.
9. Test alternative-source qualification time.
10. Evaluate reclaimed-water options.
11. Evaluate cooling redesign.
12. Map utility and power interdependence.
13. Quantify historical downtime.
14. Model future climate ranges.
15. Include water in capital approvals.
16. Price emergency water procurement.
17. Review insurance terms.
18. Review permits and discharge limits.
19. Engage basin stakeholders.
20. Report board-level metrics.
21. Test supplier substitution.
22. Maintain emergency protocols.
23. Track local household and ecosystem pressures.
24. Audit public claims against actual basin outcomes.
25. Reassess after acquisitions and major expansion.

Chapter 61

Investor and Lender Checklist

1. Is the asset location disclosed?
2. Is the basin stressed or highly variable?
3. What is the water source?
4. Is groundwater declining?
5. Is the borrower dependent on one utility?
6. Does the process require high-purity water?
7. What is the recycled-water share?
8. What capex is required for future compliance?
9. Has the asset experienced past restrictions?
10. What is the flood risk?
11. What insurance coverage exists?
12. How material is water to revenue?
13. How material is water to key suppliers?
14. Does expansion assume new water rights?
15. Are community conflicts present?
16. Is the utility financially healthy?
17. Are tariffs below sustainable cost?
18. Is desalination or transport required in stress periods?
19. Are public adaptation investments funded?
20. How does water risk alter debt service under stress?

Part XVI. Limitations, Falsifiability and Reproducibility

Chapter 62

Limitations

62.1 Data gaps

Global water data are incomplete. Reporting frequency differs across countries. Groundwater and private abstraction are especially difficult to observe. Some datasets combine measured and modelled values. The paper therefore avoids treating every global indicator as direct observation.

62.2 Spatial aggregation

National averages conceal basin-level conditions. This is a central limitation of cross-country comparisons. Facility-level decisions should use local data.

62.3 Forecast uncertainty

Climate models provide ranges rather than precise local predictions. Economic projections add further uncertainty through assumptions about adaptation, technology, prices and policy.

62.4 Causal inference

Water shocks often coincide with heat, energy shortages, conflict or macroeconomic weakness. Attribution of economic loss requires careful research design. This paper uses examples to identify transmission channels rather than claim that water alone caused every observed loss.

62.5 Corporate data

Company water disclosures differ in boundaries, assurance and definitions. Corporate examples in this paper are used to illustrate technology and strategy, not to rank company performance.

62.6 Index status

The WSRI and SWES are original proposals. They are not validated standards. No institution cited in this paper has endorsed them.

62.7 Scenario status

Scenarios are not forecasts. Plausibility scores in the scenario figure are illustrative and do not represent statistical probabilities.

Chapter 63

Falsifiability Tests

A serious framework should identify evidence that would weaken its claims.

The weak-link thesis would be weakened if average national water endowment consistently predicts economic water-loss outcomes better than the lowest-performing resilience domain.

The source-diversity thesis would be weakened if cities with multiple independent supplies show no better drought performance after controlling for income, storage and governance.

The virtual-water diversification thesis would be weakened if supplier hydrological correlation does not improve prediction of food-import volatility.

The financial-materiality thesis would be weakened if basin-level water exposure shows no relationship with credit, insurance or asset performance after relevant controls.

The water-sensitive industrial-location thesis would be weakened if water reliability has no measurable effect on location decisions in high-dependence sectors after power, labour and logistics are controlled.

The reuse-resilience thesis would be weakened if high reuse rates do not improve continuity during drought after accounting for storage and utility reliability.

The ecosystem-buffer thesis would be weakened if watershed condition does not reduce flood or drought losses after controlling for engineered infrastructure.

Chapter 64

Reproducibility Protocol

Researchers replicating this paper should record the following for each quantitative claim:

1. Source institution and publication.
2. Publication date and data year.
3. Geographic unit.
4. Definition of water variable.
5. Whether the value is measured, estimated or modelled.
6. Unit conversion.
7. Scenario assumptions if projected.
8. Any confidence range.
9. Any methodological caveat stated by the source.
10. Access date where online data are updated.

For facility studies, latitude and longitude or a consistent basin identifier should be added where disclosure and privacy rules permit.

Chapter 65

Source Hierarchy and Claim Register

Major claims in this monograph are based on the following source classes.

Claim area	Preferred source	Status	Primary caveat
Global hydrology 2025	WMO	Observed/model synthesis	Coverage varies by region
WASH access	WHO/UNICEF JMP	Estimated current coverage	Country data availability differs
Water stress	WRI Aqueduct	Modelled risk indicator	Screening tool, not direct outcome
Agricultural withdrawals	FAO AQUASTAT	Statistical synthesis	Reporting years and definitions vary
Economic losses	World Bank, GCEW, OECD	Modelled projections	Models are not directly comparable
Data-centre electricity	IEA	Modelled projection	Water impact depends on cooling and power mix
Transboundary cooperation	UNECE/UNESCO	Country reporting	Agreement quality differs
Corporate water measures	Company reports	Self-reported	Assurance varies

Part XVII. Publication Audit

Chapter 66

Factual Audit Requirements

Before publication, the following checks are required.

- Verify the WMO 2025 hydrological statements against the September 2026 publication.
- Verify WASH coverage and unserved-population figures against the 2025 JMP report.
- Preserve WRI's caveat that Aqueduct is a prioritisation tool.
- Keep FAO withdrawal shares separate from consumptive-use claims.
- Keep World Bank, GCEW and OECD economic estimates separated by model and vintage.
- Label IEA data-centre figures as electricity demand rather than direct water use.
- Label Microsoft, Intel and TSMC operational figures as company-reported.
- Keep Panama Canal 2023-24 restrictions separate from 2026 operational conditions.
- Label all scenarios as stress tests.
- Label the WSRI and SWES as original, unvalidated frameworks.

Chapter 67

Quantitative Audit Requirements

- Recalculate all figure labels.
- Confirm sectoral withdrawal shares sum to 100 percent in the chosen FAO aggregate.
- Confirm 2015 and 2024 WASH coverage values.
- Confirm 2.1 billion, 3.4 billion and 1.7 billion unserved figures.
- Confirm the 25-country and four-billion-person WRI exposure statements.
- Confirm data-centre electricity values and units.
- Confirm economic-loss ranges are not presented as one combined forecast.
- Confirm Panama Canal trade share and drought-era transit values.
- Confirm equations render correctly.

Chapter 68

Layout Audit Requirements

- No blank first page.
- No blank content pages.
- No clipped text or tables.
- No headings split into unreadable fragments.
- No orphaned figure captions.
- No unresolved citation keys.
- No broken bibliography entries.
- Fonts embedded.
- Images legible at print resolution.
- Page numbers consistent.
- Title page unnumbered.
- Table of contents complete.
- Equations and symbols render without substitution errors.

Chapter 69

Conclusion

Water is becoming a more visible constraint on growth because economic systems are becoming more interconnected at the same time that the hydrological cycle is becoming more volatile.

The evidence does not support a single narrative of universal water scarcity. Some regions face chronic shortage. Others face flood. Many face pollution, infrastructure gaps, groundwater depletion or seasonal volatility. The common factor is that water risk is local in origin but increasingly systemic in consequence.

The latest WMO evidence shows that abnormal river-flow conditions, declining terrestrial water storage and glacier loss are not isolated observations. (World Meteorological Organization, 2026) WHO and UNICEF show that billions of people still lack safely managed services. (WHO and UNICEF, 2025) WRI shows that severe water stress is concentrated across a substantial share of the world's population. (Kuzma et al., 2023) OECD shows that water risk is entering financial-stability analysis. (OECD, 2025) IEA analysis shows that new electricity-intensive systems such as AI data centres are adding concentrated infrastructure demand in specific locations. (International Energy Agency, 2025b, 2026)

These findings point toward a broader economic-security framework.

Water security depends on more than endowment. It depends on storage, infrastructure, quality, allocation, ecosystems, finance, data and cooperation. A water-abundant country can be economically exposed if networks fail. A water-scarce country can remain resilient if it has diversified supply, disciplined demand, strong institutions and reliable infrastructure.

The central policy objective should therefore be resilient allocation, not maximum extraction.

For governments, this means integrating water into industrial, food, energy, housing and digital policy. For companies, it means mapping basin-specific dependencies and testing continuity. For financial institutions, it means connecting assets and borrowers to physical water systems. For researchers, it means linking hydrology to economic networks with greater spatial precision.

The strategic principle is straightforward.

Water security is economic security because water is the enabling input beneath food, health, energy, industry, cities, trade and ecosystems.

The systems best prepared for the next decade will not be those that assume historical reliability will continue. They will be those that measure their dependencies, protect sources, maintain infrastructure, diversify supply, reuse water, allocate transparently and preserve institutional capacity to act before scarcity becomes crisis.

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