

# Adaptation through Water and Applied Limnology: Connecting the World Economic Forum Report to Ten Principles from an Applied Limnological Perspective

Chee Kong Yap<sup>\*</sup>

Department of Biology, Faculty of Science, University Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia

**Abstract:** The World Economic Forum's 2025 report, *Adaptation through Water: Mobilising the Private Sector for Climate Adaptation in Southeast Asia*, provides a practical basis for linking water risks to private-sector action. This commentary contributes an operational synthesis of that agenda with ten established principles of applied limnology. The principles progress from aquatic connections and catchment diagnosis to hydrology, residence time, thermal structure, nutrients, sediments, biological responses, interacting stressors and adaptive management. Their contribution is to connect project benefits with the ecological processes that can sustain or undermine those benefits. Flood protection, storage, reuse and nature interventions are therefore assessed through both human risk reduction and receiving ecosystem condition. A proposed assessment framework distinguishes core baseline evidence from investigations triggered by specific risks and links monitoring results to named corrective actions. A hypothetical retention pond illustrates how managers could prioritise flow, nutrient loads, oxygen and biological indicators before expanding the monitoring programme. The framework is a conceptual proposal, not an empirically validated scoring system. Its central argument is that adaptation requires evidence of durable ecological function, with explicit attention to downstream effects, seasonal variability and delayed responses.

**Keywords:** Applied limnology, Catchment, Climate adaptation, Eutrophication, Flood, Lake, River, Southeast Asia, Water quality, Wetland.

## 1. INTRODUCTION

Water adaptation changes the inland waters people depend on. A reservoir, flood diversion or reuse scheme can alter flows, water quality and habitats beyond its immediate footprint. Limnology provides the physical, chemical and biological basis for examining these changes across connected catchments and receiving waters (Soranno *et al.*, 2010; Williamson *et al.*, 2009). Climate adaptation therefore needs to consider ecosystem condition alongside water availability and protection from hazards.

The World Economic Forum (2025) frames water risks as too much, too little, or too dirty and links adaptation to flood reduction, water optimisation and circularity, finance, and water-and-nature innovation. This is a useful investment perspective. A complementary ecological question is whether each intervention maintains the processes that make water usable and aquatic habitats functional through changing seasons and extreme events.

The original contribution of this commentary is an operational synthesis rather than a claim to new limnological theory. It translates ten established principles into a linked sequence of diagnosis, process assessment, ecological verification and corrective

action. It also proposes priorities for collecting evidence in practical projects. The aim is to extend an investment agenda with measurable ecological safeguards and explicit responsibilities, while recognising the possibility of maladaptation described by the Intergovernmental Panel on Climate Change (2022). The framework is intended to guide project design and subsequent testing; it has not been empirically validated.

## 2. CRITICAL COMPARISON WITH ESTABLISHED LIMNOLOGICAL APPROACHES

The comparison concerns purpose and application. The WEF report offers an agenda for mobilising private-sector adaptation, including nature, efficiency, digital tools, and finance (World Economic Forum, 2025). These priorities are compatible with ecological management. The question developed here is how a project team can translate them into testable outcomes for inland waters. The following safeguards are the author's proposed operational extension, not a claim that the report rejects ecosystem protection.

Several foundations already exist. Landscape limnology links ecosystem condition to catchment characteristics and spatial context (Soranno *et al.*, 2010). The natural flow regime provides a basis for assessing ecological consequences of altered discharge (Poff *et al.*, 1997). Studies of lakes as climate sentinels show why physical and biological responses must be interpreted together (Adrian *et al.*,

<sup>\*</sup>Address correspondence to this author at the Department of Biology, Faculty of Science, University Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia; E-mail: yapchee@upm.edu.my

2009; Williamson *et al.*, 2009). The ten principles bring these approaches into one project assessment sequence; their novelty lies in the synthesis and application, not in the individual concepts.

The proposed extension makes three comparisons explicit. First, the assessment boundary includes upstream sources and downstream receiving waters rather than ending at the financed asset. Second, performance combines the intended service, such as flood attenuation or water supply, with process indicators and ecological responses. Third, assessment continues through operation so that sediment release, oxygen loss, biological change and slow recovery are not obscured by an initially successful engineering result. Recovery after nutrient reduction can be delayed or incomplete, which makes the time horizon consequential (McCrackin *et al.*, 2017).

This extension also has limits. A comprehensive ecological diagnosis requires skills, funding and locally suitable reference conditions. Applying every indicator to every project would be inefficient and could conceal the most important risks. Section 4 therefore proposes a staged assessment in which all projects receive a core baseline, while specific exposure pathways determine additional investigations and operational triggers. The framework complements economic and social appraisal; it does not provide a universal numerical score or a substitute for statutory assessment. Coastal examples within a broader water agenda require additional marine and coastal expertise beyond the inland water emphasis of this commentary.

### 3. TEN PRINCIPLES OF APPLIED LIMNOLOGY FOR ADAPTATION THROUGH WATER

The principles follow a diagnostic progression: Principles 1 and 2 define the assessment boundary and sources; Principles 3 to 7 examine flow and material processing; Principles 8 and 9 test ecological response and interacting risks; Principle 10 assigns monitoring and corrective action. Each principle is presented as a process followed by its distinct implication for project decisions.

#### 3.1. Principle 1: Inland Waters are Connected Ecological Systems

Inland waters exchange water, energy and materials with their catchments, atmosphere, groundwater and downstream habitats. The River Continuum Concept describes longitudinal changes in river processes and communities (Vannote *et al.*, 1980), while landscape limnology places individual waters within wider spatial relationships (Soranno *et al.*, 2010). Lakes and reservoirs also integrate catchment and climate signals (Williamson *et al.*, 2009).

The distinct decision is to define the hydrological influence area of an intervention. Assess how a barrier, dam or wetland changes the movement of water, sediment and organisms across that area. A local reduction in flood exposure should be checked for downstream transfer of risk, and a gain in storage should be checked for lost ecological connections.

Figure 1 links the hydrological network to the boundaries within which project effects should be assessed.

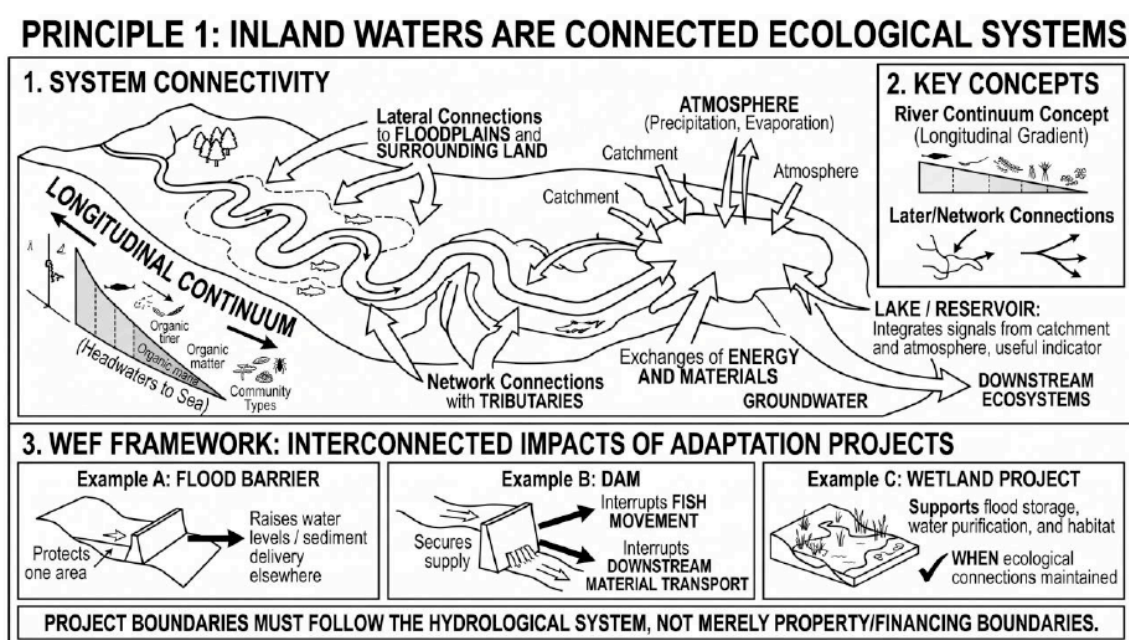


**Figure 1:** Connected inland waters and project influence boundaries. The schematic distinguishes hydrological connections from the decision to assess impacts across the network (Vannote *et al.*, 1980; Soranno *et al.*, 2010).

### 3.2. Principle 2: The Catchment is the Basic Unit of Diagnosis and Management

Catchment land cover, soils, geology, agriculture, urban runoff, wastewater and industry shape inflow quantity and quality. Diagnosis therefore begins with the sources outside the receiving water. Treating a lake while external loading continues cannot address the whole problem. Recovery may also remain slow after inputs decline because ecosystem responses retain the effects of earlier degradation (McCrackin *et al.*, 2017).

The distinct decision is which sources must be controlled before, or alongside, construction. Map abstraction, runoff, erosion and relevant nutrient or contaminant sources; identify who can change them. Catchment stewardship should be costed as part of the intervention rather than left outside the project's financial boundary.

Figure 2 locates receiving water conditions within the catchment sources that must be diagnosed before design.

### 3.3. Principle 3: Hydrology is a Master Control of Ecological Condition

Flow magnitude, timing, duration, frequency and rate of change influence channel habitat and aquatic life cycles (Poff *et al.*, 1997). Floods can renew floodplain habitats and move materials, whereas drought can reduce refuges and interrupt connections.

Ecologically useful variation must be distinguished from exposure that endangers people.

The distinct decision is the acceptable alteration of the flow regime. Compare design and operating scenarios with environmental flow needs and floodplain exchange. Forecasting, barriers and diversions should reduce harmful exposure while maintaining necessary flow cues and habitat renewal, rather than treating every flood pulse as an ecological failure.

Figure 3 links flow variation to habitat maintenance and ecological flow requirements.

### 3.4. Principle 4: Residence Time and Connectivity Regulate Processing and Risk

Residence time affects opportunities for settling, transformation and phytoplankton growth. Longer retention can provide useful processing, but may also favour warming and oxygen depletion; rapid flushing can reduce local accumulation while exporting material downstream. Connectivity separately determines pathways for organisms, sediment and solutes. Their effects depend on the water body's characteristics.

The distinct decision is how much retention and exchange the design can sustain. Estimate seasonal inflow, outflow and storage change and identify connected habitats and contaminant pathways. Use these budgets to evaluate operating alternatives. Neither maximum retention nor maximum conveyance is an ecological objective in itself.

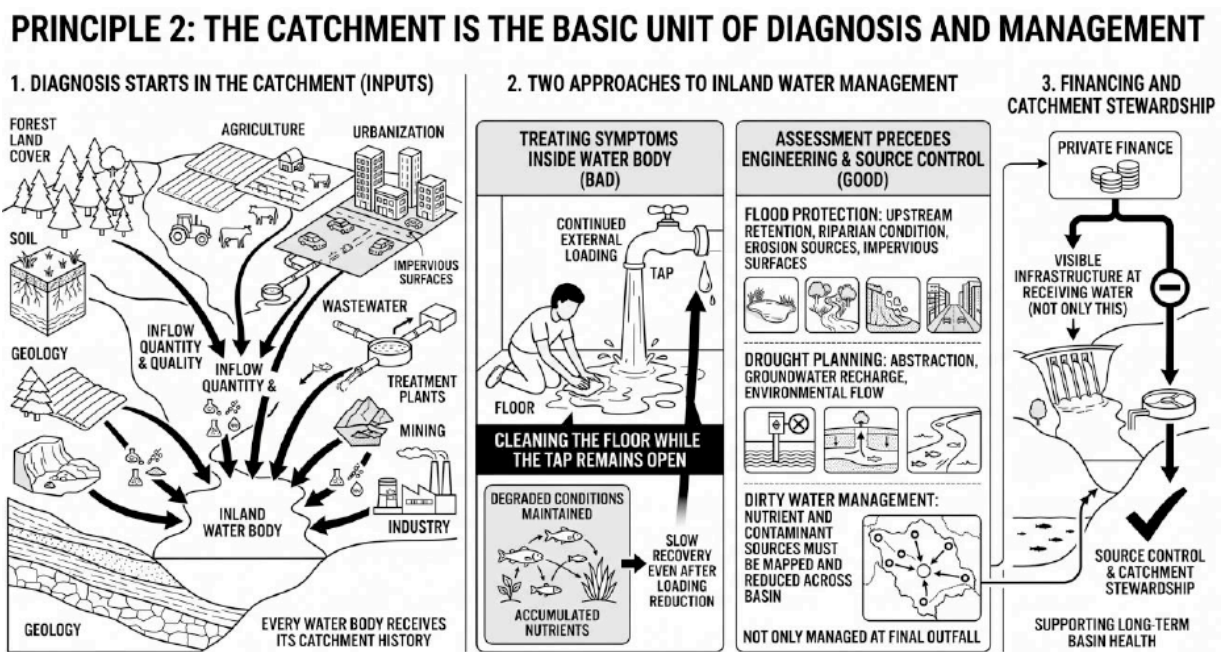


**Figure 2:** Catchment diagnosis before intervention. Source inputs, inflow loads and receiving water response guide source control and restoration planning (Soranno *et al.*, 2010; McCrackin *et al.*, 2017).

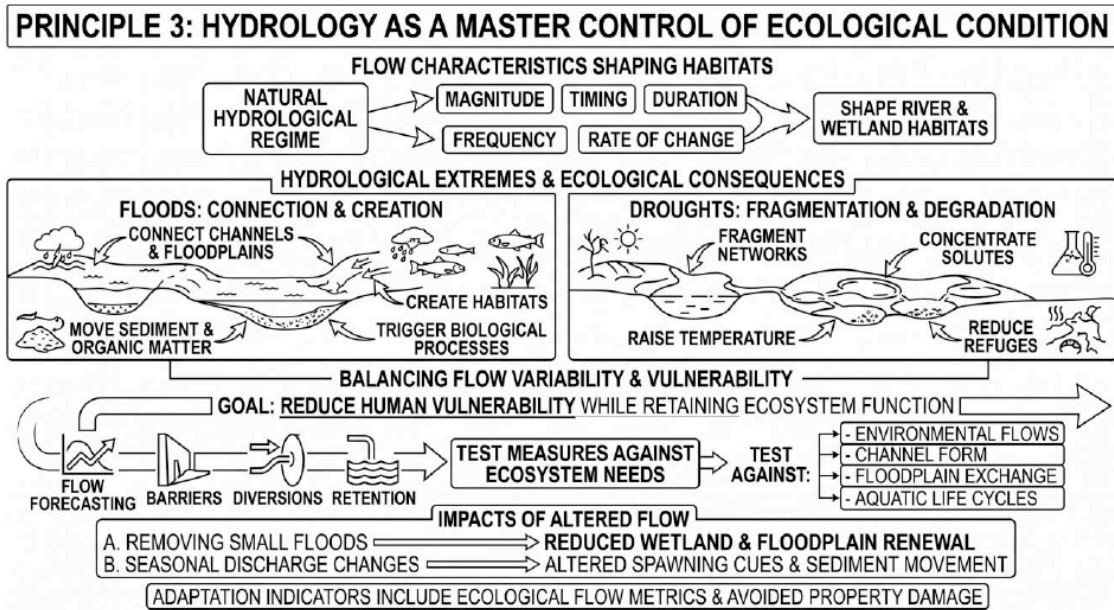


**Figure 3:** Hydrology and ecological flow requirements. Flow variation supports habitat processes, while project assessment seeks to reduce dangerous exposure without unnecessary ecological disruption (Poff *et al.*, 1997).

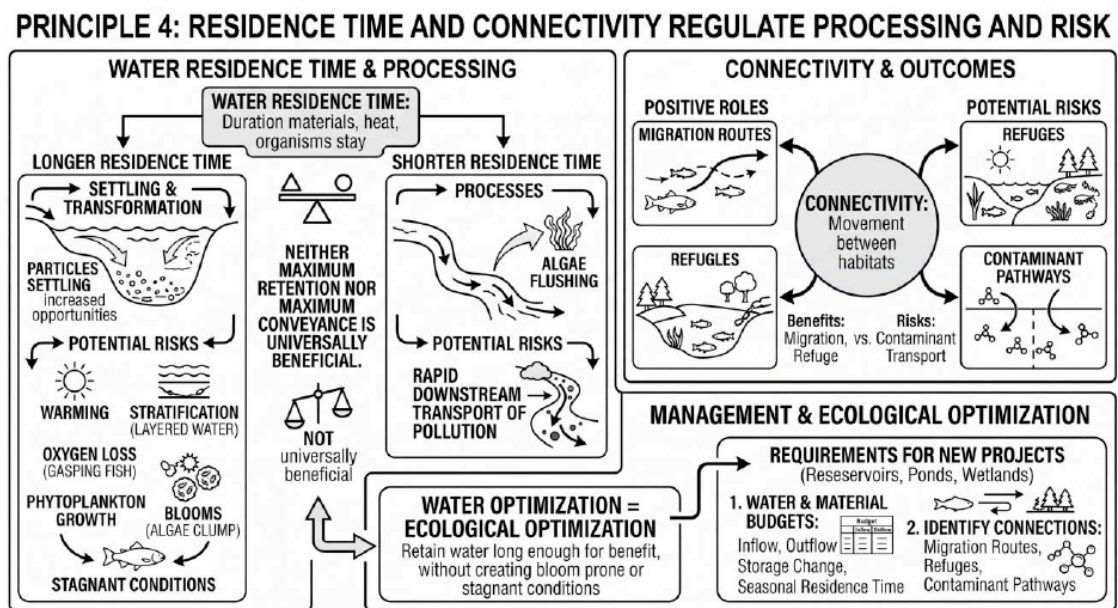


**Figure 4:** Residence time and connectivity. Retention and exchange can provide benefits or create accumulated and downstream risks; outcomes depend on system conditions. This is a conceptual assessment pathway, not a quantified predictive model.

Figure 4 identifies the tradeoff between useful retention, material processing and accumulated or exported risk.

### 3.5. Principle 5: Thermal Structure, Oxygen and Redox Processes Control Water Quality

Temperature affects water density and metabolic oxygen demand. Where depth and mixing conditions allow stratification, bottom waters may become isolated and oxygen depleted. Changes in sediment redox can then mobilise phosphorus, iron, manganese and some contaminants. Surface measurements alone can miss

these conditions. Therefore, interpret lake responses to climate using physical and biological evidence together (Adrian *et al.*, 2009; Williamson *et al.*, 2009).

The distinct decision is whether a surface sample adequately represents usable water. Where stratification is plausible, profile temperature and dissolved oxygen and record depth and mixing across seasons. Evidence of deterioration should inform withdrawal depth, inflow management, aeration or nutrient control; these options require evaluation for the particular reservoir or pond.

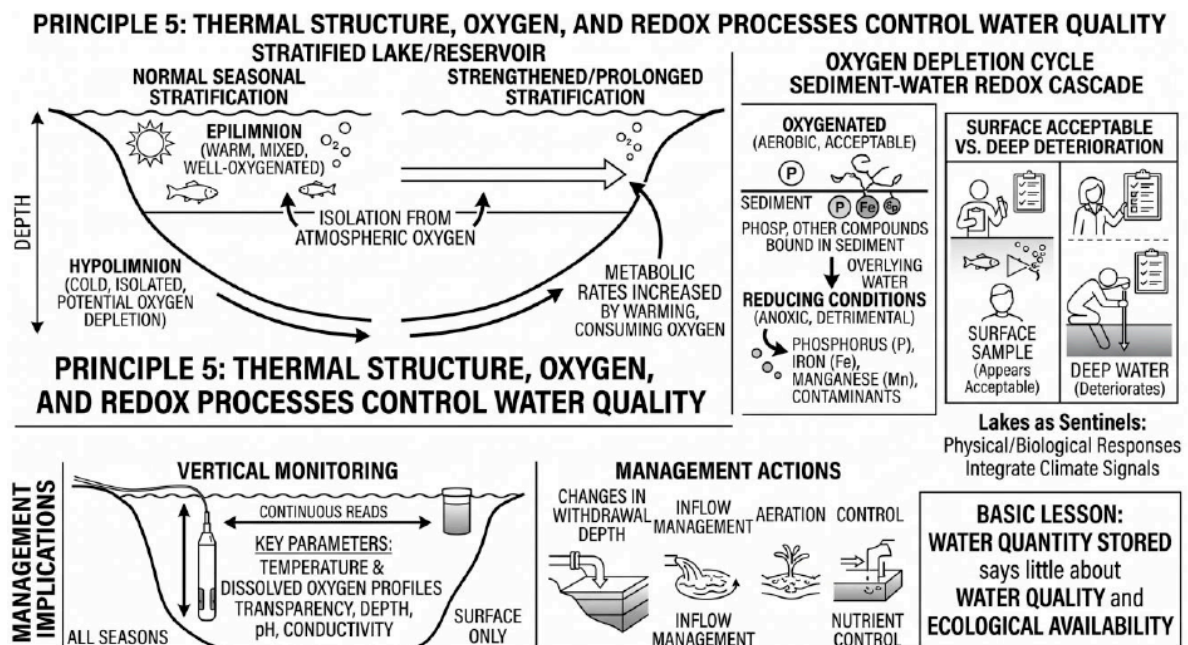


**Figure 5:** Thermal structure, oxygen and redox. The illustrated pathway is relevant where stratification restricts mixing; warming does not imply identical responses in all inland waters (Adrian *et al.*, 2009; Williamson *et al.*, 2009).

Figure 5 shows why thermal structure and oxygen require depth-resolved assessment where stratification occurs.

### 3.6. Principle 6: Nutrient Loading Links Water use with Eutrophication

Excessive nutrient loading can promote algal growth, oxygen depletion and habitat change. In the Lake 227 experiment, reducing nitrogen inputs without reducing phosphorus did not reverse eutrophication (Schindler *et al.*, 2008). This supports careful attention

to phosphorus, rather than assuming one nutrient rule applies to every water body. Hoyer and Canfield (2022) also show that phosphorus–chlorophyll relationships must be interpreted with local limiting factors, including flushing and light.

The distinct decision is whether the receiving system can accommodate the proposed load. Quantify nutrient inputs and outputs alongside chlorophyll *a*, transparency, oxygen and phytoplankton composition. Reuse and treatment wetlands must be assessed for their material balances and receiving water response;

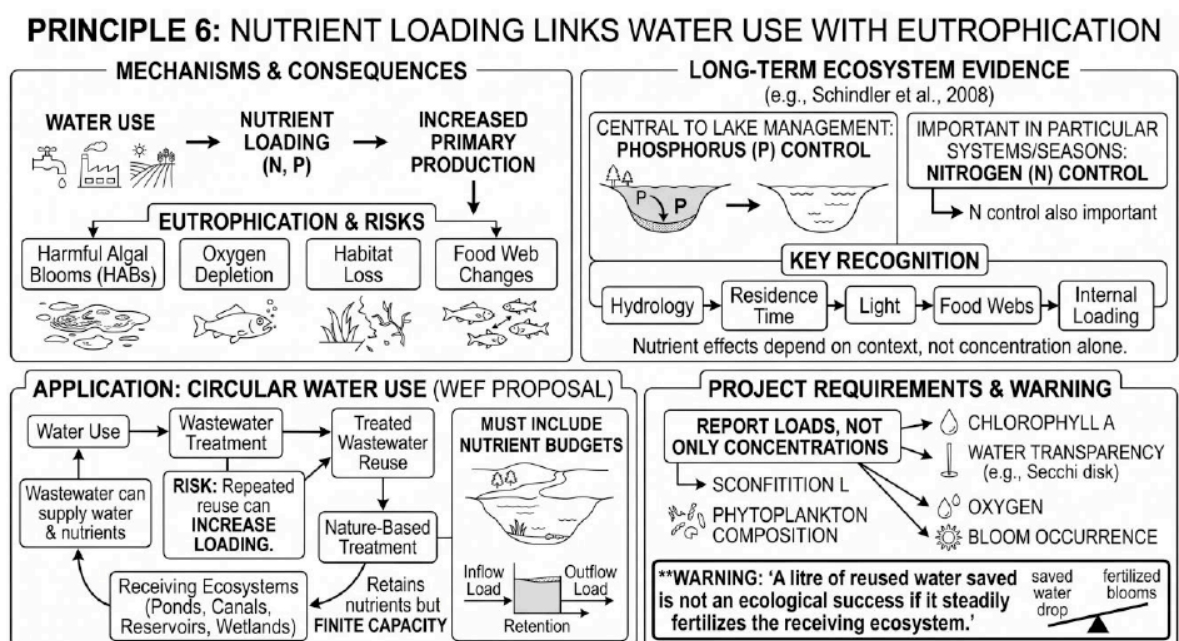


**Figure 6:** Nutrient loading and ecological response. The assessment uses loads and biological indicators rather than water savings alone (Schindler *et al.*, 2008; Hoyer & Canfield, 2022).

reduced abstraction alone does not demonstrate an ecological benefit.

Figure 6 links nutrient loading with biological response and the evaluation of water reuse.

### 3.7. Principle 7: Sediments are both Environmental Memory and Internal Source

Sediments store mineral particles, organic matter, nutrients, contaminants and biological remains. Suitable sediment cores can record earlier environmental conditions. Deposited material may also be resuspended by floods, wind, dredging or organisms, while changed oxygen and redox conditions can alter release to the water. This potential legacy helps explain why reducing external inputs may not produce immediate recovery (McCrackin *et al.*, 2017).

The distinct decision is whether disturbing or reconnecting sediment creates an additional exposure pathway. Before dredging, diversion or wetland reconnection, examine erosional and depositional zones for grain size, organic matter, nutrients and contaminants relevant to the catchment. After major floods, determine where new material accumulated. Detailed sediment chemistry is prioritised where sources or planned disturbance indicate a plausible risk.

Figure 7 separates the sediment record of past inputs from potential present release under disturbance.

### 3.8. Principle 8: Aquatic Organisms Integrate Exposure and Ecological Function

Organisms complement chemical snapshots because growth, reproduction, survival and community composition reflect conditions over time. Phytoplankton, macrophytes, benthic invertebrates and fish provide different information about productivity, habitat, sediment exposure and connectivity. Indicator selection should match the habitat and pressure, rather than assuming any one group represents the whole ecosystem (Dudgeon *et al.*, 2006; Reid *et al.*, 2019).

The distinct decision is which biological response demonstrates the intended ecological outcome. Establish seasonal baseline communities and suitable local comparisons before implementation, then repeat the same methods during operation. Sensors and remote observations should be field-checked, while new canals and transfers should be screened for risks of introducing or spreading invasive organisms.

Figure 8 shows how biological responses complement measurements of chemistry and habitat.

### 3.9. Principle 9: Multiple Stressors can Produce Threshold Surprises and Unequal Outcomes

Warming, altered flow, pollution, salinisation and habitat change may operate together, with cumulative effects on freshwater biodiversity (Reid *et al.*, 2019). Drought can coincide with heat and reduced dilution, while floods can carry several pollutant classes. Responses may be nonlinear, but a threshold should not be claimed without appropriate evidence.

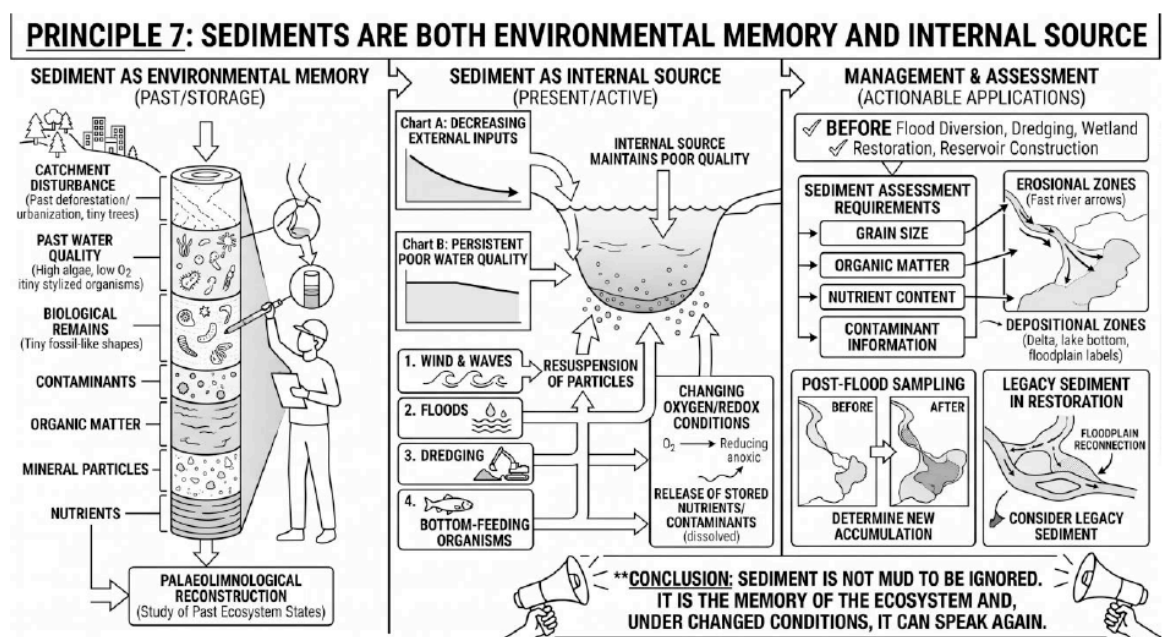


**Figure 7:** Sediment storage and possible legacy release. Disturbance and changing redox can require targeted sediment assessment; the schematic does not imply that every sediment deposit releases contaminants (McCrackin *et al.*, 2017).

## PRINCIPLE 8: AQUATIC ORGANISMS INTEGRATE EXPOSURE AND ECOLOGICAL FUNCTION

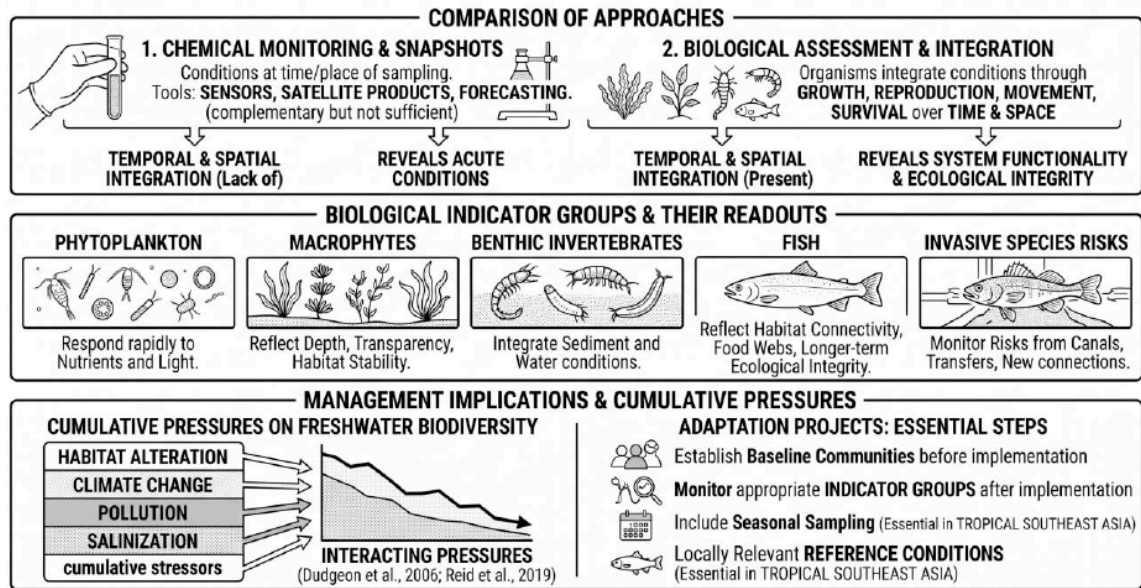


**Figure 8:** Biological evidence of ecological function. Indicator groups are selected according to habitat, exposure pathways and appropriate local reference conditions (Dudgeon *et al.*, 2006; Reid *et al.*, 2019).

The distinct decision is whether combined scenarios or displaced impacts make a seemingly acceptable design unsafe for particular receptors. Test relevant combinations of climate, pollution and operating failure, and identify exposed communities, fisheries and downstream habitats. Document uncertainty and contingency actions rather than assuming a design that performs under one scenario will perform under all future conditions.

Figure 9 connects interacting pressures with ecological thresholds and the distribution of risk.

### 3.10. Principle 10: Long-Term Monitoring and Adaptive Management Complete the Intervention

Freshwater conditions vary across days, seasons and years. Short records can confuse natural variation with project effects, while longer records can identify trends, delayed responses, and recovery (Adrian *et al.*, 2009; McCrackin *et al.*, 2017). A credible assessment therefore needs a baseline, consistent methods and a strategy for distinguishing an intervention effect from wider catchment change.

## PRINCIPLE 9: MULTIPLE STRESSORS CAN PRODUCE THRESHOLDS SURPRISES AND UNEQUAL OUTCOMES

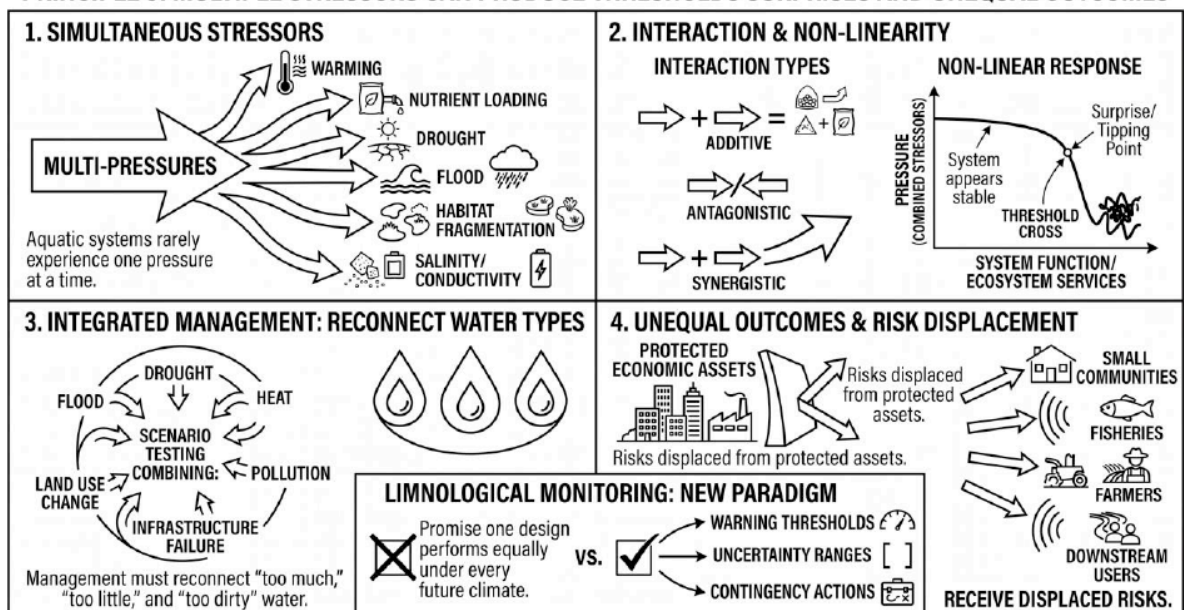


**Figure 9:** Interacting pressures, possible thresholds and risk distribution. Combined scenarios are assessed together with uncertainty and downstream exposure (Reid *et al.*, 2019).

### Principle 10: Long term monitoring and adaptive management complete the intervention

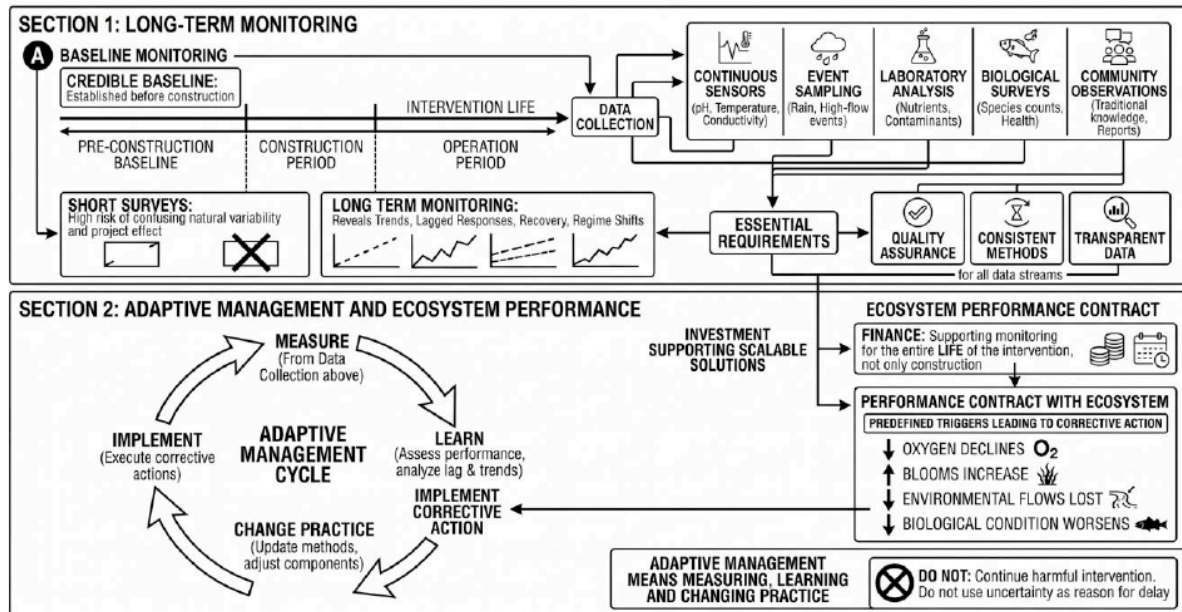


**Figure 10:** Monitoring and adaptive management. Baseline evidence, repeated assessment and assigned corrective actions form a continuing review cycle (Adrian *et al.*, 2009; McCrackin *et al.*, 2017).

The distinct decision is who acts when evidence departs from the agreed target. Specify monitoring costs, responsible organisations, review intervals and corrective actions before operation. Use sensors, event sampling, laboratory analysis and biological surveys according to the risks identified. Where feasible, compare changes with an unaffected reference site. An operational trigger initiates diagnosis and a defined response; uncertainty is recorded without excusing preventable harm.

Figure 10 closes the assessment sequence by linking monitoring, evaluation and corrective action.

#### 4. PRIORITISING EVIDENCE IN PRACTICAL ADAPTATION PROJECTS

Table 1 is a proposed project screening framework, not a universal minimum standard or validated score. Its intervention categories distinguish physical projects from enabling functions such as finance and digital monitoring; water storage is an intervention considered here rather than a separately named WEF opportunity. Indicator priority should follow the proposed change, the exposure pathway, the severity and reversibility of potential harm, sensitive downstream users, applicable requirements and uncertainty. Existing good-quality data can reduce duplication, but missing data on a consequential risk requires investigation rather than automatic approval.

A core evidence package is required for each project: define the catchment and receiving waters, document the intervention and expected flow changes,

identify sensitive users and habitats, compile a baseline, and select a small set of water quality and biological indicators relevant to the local system. Temperature, dissolved oxygen, pH, conductivity and appropriate hydrological observations are useful starting measurements. Nutrients, turbidity and representative biological groups should be selected where the identified pressures make them informative. This package must cover relevant wet and dry conditions and include an event sampling plan. An annual baseline is preferable when feasible; a short survey alone cannot establish rare event performance.

Targeted investigations are then added where the mechanism requires them. A deep reservoir needs temperature and oxygen profiles; a reuse scheme needs water and solute mass balances; sediment disturbance near known pollution sources needs sediment characterisation; and a transfer between previously separated waters needs connectivity and invasive species assessment. Studies with higher costs receive priority when consequences could be severe or irreversible, or when uncertainty prevents a defensible decision. Additional research can follow after these decision-critical gaps are addressed. The categories determine the order of evidence collection, not an exemption from relevant safeguards.

Implementation proceeds through four stages. At screening, map the sources, receptors and legal requirements. Before design approval or commissioning, establish baseline and targeted evidence and agree on acceptable outcomes. During

operation, monitor selected indicators at appropriate sites, depths and intervals, with extra sampling during identified high-risk seasons or events. At scheduled review, compare results with the baseline, suitable reference conditions and agreed limits, examine competing explanations and implement corrective measures. Where possible, a reference site and repeated observations before and after intervention improve attribution. Regional records and scenario analysis are also needed where local monitoring cannot represent extreme floods or droughts.

Consider a hypothetical urban retention pond receiving nutrient-rich runoff. The first priority is a wet- and dry-season water budget with inflow and outflow nutrient loads, water-level and dissolved-oxygen observations, supported by rainfall and operational records. Where feasible, include measurements around dawn to capture low oxygen conditions and temperature profiles if depth suggests stratification. Rising chlorophyll *a* or recurrent oxygen deterioration would prompt more detailed phytoplankton and mixing assessment, followed by evaluation of source control and pond operation. Sediment contaminant analysis becomes decision-critical if source mapping identifies contamination or dredging is planned. These are proposed priorities for a scenario, not measurements from an actual project.

The monitoring plan must name the operator, reviewer and party funding corrective action. Thresholds are set from applicable limits, local ecological objectives, baseline variability, relevant species requirements and measurement uncertainty; a single oxygen or nutrient threshold is not proposed for all waters. An agreed trigger should state the indicator, site, depth or timing, verification procedure, response deadline and action. For example, recurrent departure from a locally agreed oxygen objective could trigger confirmation sampling and a review of nutrient inputs, mixing and withdrawal operation. Routine review should assess whether benefits and burdens remain fairly distributed. This links Table 1 to the accountable adaptive management proposed in Principle 10.

## 5. GENERAL DISCUSSION AND LIMITATIONS

The proposed synthesis changes the evidence used to judge a project, not the underlying purpose of adaptation. Human safety, dependable supply and economic feasibility remain essential. Limnology adds a test of whether those benefits rely on degradation elsewhere or emerge at the expense of future ecosystem function. Floodplain renewal, usable oxygenated storage, and receiving-water integrity should be expressed as project-specific objectives, with trade-offs made visible rather than assumed away. This follows the wider warning that adaptation can

**Table 1: Proposed Priorities for Evidence Collection and Operational Decisions in Water Adaptation Projects. Core Evidence Applies to all Projects; Targeted Evidence is Added where the Intervention or Exposure Pathway Creates the Specified Risk**

| Project or Enabling Function | Primary Ecological Question                                            | Priority Evidence and Timing                                                                                                                           | Decision and Operational Response                                                                                                      |
|------------------------------|------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------|
| Flood reduction              | How will flow, sediment movement and floodplain exchange change?       | Core: flow and level baseline, habitats and exposed users. Targeted before design: floodplain exchange, sediment and biological response.              | Assess local and downstream effects. Agreed departures from ecological flow or habitat objectives prompt operating or design review.   |
| Water storage                | Will retention, stratification or oxygen loss compromise usable water? | Core: water budget and seasonal quality. Targeted before operation: residence time, depth profiles, nutrients and chlorophyll <i>a</i> .               | Evaluate quality alongside volume. Recurrent oxygen deterioration or bloom indicators prompt review of inputs and reservoir operation. |
| Water circularity            | Where will salts, nutrients and relevant contaminants accumulate?      | Core: sources, receivers and intended use. Targeted before commissioning: water and material balances, residuals and applicable exposure requirements. | Assess receiving water effects and residual disposal. Load or quality departures trigger treatment and reuse operation review.         |
| Nature solutions             | Will retention, habitat and water quality benefits persist?            | Core: hydrology, habitat baseline and maintenance plan. Targeted: sediment, nutrient and biological evidence according to the site's pressures.        | Verify intended benefits through time. Loss of storage or habitat function triggers maintenance and source control review.             |
| Adaptation finance           | Who is responsible for ecological performance and correction?          | Core before approval: baseline targets, funded monitoring, review arrangements and named responsibilities.                                             | Require reporting and corrective action when agreed targets are missed; retain resources for monitoring throughout operation.          |
| Digital monitoring           | Do observations support reliable ecological decisions?                 | Core before use: calibration, field comparisons and uncertainty. Targeted: depth, event and biological checks where relevant.                          | Confirm anomalous signals and examine sensor or model error before operational decisions; combine digital and field evidence.          |

encounter ecological limits or produce maladaptation (Intergovernmental Panel on Climate Change, 2022).

The framework also separates ecological assessment from the health requirements of a particular water use. World Health Organisation (2006) addresses agricultural wastewater use, while the World Health Organisation (2017) provides guidance for potable reuse. Those documents do not impose identical requirements. A project must apply the guidance relevant to its intended use and also examine material loads, residuals and receiving ecosystem responses. Neither a successful treatment process nor a high reuse percentage, by itself, verifies ecological benefit.

This commentary does not provide a systematic review, a tested scoring model or measured outcomes from an adaptation project. Some cited conceptual approaches and experiments were developed outside tropical Southeast Asia, so local hydrology, mixing, biological communities and institutional capacity require evaluation before transfer. Validation should compare projects assessed with the proposed sequence against documented alternatives, testing whether it identifies consequential risks, supports timely corrective action and remains affordable. The hypothetical pond example demonstrates a possible decision process, not evidence of effectiveness.

My basic metaphor remains simple. A catchment is the body, and its rivers are the veins; lakes, reservoirs, and wetlands are organs that store, transform, and release water and materials. Looking only at the volume moving through them misses the oxygen, sediments, nutrients and organisms that determine their condition. Basic is still basic. Go to the water, measure it properly, return in different seasons and compare the evidence before and after intervention. The practical discipline is to choose measurements that can change a decision, while retaining responsibility for what that decision does downstream.

## 6. CONCLUSION

The WEF adaptation agenda can be strengthened by linking intended project services with the ecological processes that sustain them. This commentary synthesises ten established limnological principles, organised from catchment diagnosis to operational review. It makes project boundaries, process indicators, biological evidence and delayed responses explicit without claiming that the principles are new ecological theory.

The proposed framework prioritises a core baseline, adds investigations based on consequential exposure pathways, and links agreed targets to responsible

parties and corrective action. Table 1 and the hypothetical retention pond show how this could guide practical projects. The framework now requires local testing and refinement. Its value should ultimately be judged by whether it helps reduce human vulnerability while maintaining ecological function and avoiding the transfer of risks to downstream waters and communities.

## DECLARATION OF AI-ASSISTED EDITING

Generative AI assisted with language refinement, structural revision, formatting, preparation of the reviewer response and bibliographic checking. The ten revised conceptual figures were produced programmatically from the author's explanatory framework with AI-assisted drafting of labels and layout. They present proposed relationships and assessment steps, not new measurements or empirical model outputs. The author retains responsibility for scientific interpretation, source verification and the final submitted manuscript.

## CONFLICTS OF INTEREST STATEMENT

The author declared no conflicts of interest.

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