

REVIEW

Research on Water Resources Health Diagnosis and Environmental Management System for Carbon Neutrality Construction

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ABSTRACT

Water resources health diagnosis is increasingly recognized as a critical tool. It should not only guide the preservation of water volume, quality, and ecological integrity but also assess the viability of carbon-neutral development pathways. But current research tends to consider water health assessment and carbon-neutrality planning as separate endeavors, which results in imprecise boundaries, disjointed metrics, and a weak linkage between diagnostic outcomes and testable management actions. This review brings together indicator systems, diagnostic systems, and environmental management systems architectures that make it possible to have integrated water-carbon governance. We define fundamental concepts and delimiting decisions followed by the examination of indicator designs across the hydrological regime, water quality, ecological integrity, service performance, resilience, and carbon-related measures, including intensity of energy/emissions, emissions caused by the watershed process of wastewater treatment, as well as the potential sink of the watershed. We compare diagnostic methods, such as composite indices and multi-criteria decision analysis, data-driven early-warning models, process-based and integrated simulations, as well as uncertainty-aware robustness models. Here, based on this synthesis, we suggest an environmental management systems (EMS)-based pathway, which connects the setting of the baseline, the diagnosis, the design of the intervention portfolio, and the measurement-reporting-verification into the closed-loop adaptive cycle. Digital enablement, comprising Internet of Things (IoT) monitoring, remote sensing, data fusion, optimization, and digital twins, is considered a viable way of

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scaling implementation, subject to interoperability, validation, and model governance. Among the major gaps, there are causal attribution to outcomes, cross-scale coupling of facility emissions and basin health, propagation of uncertainty in a coupled model, and credible Measurement, Reporting, and Verification (MRV) of non-CO₂ gases and nature-based removals. The review gives a roadmap to normalize core metrics and fast-deployable systems to protect the health of the water resources and give verifiable progress towards carbon neutrality.

Keywords: Water Resources Health; Carbon Neutrality; Environmental Management System; MRV; Digital Twin

1. Introduction

Water resources are now being considered not only by the amount of water supply, but also by their capacity to maintain ecological processes, human health, extreme buffering, and provide stable services under the increasing environmental change^[1]. The pressures facing most basins are multifaceted and often synergistic: (1) climate-induced precipitation changes that affect runoff and groundwater recharge; (2) urbanization and industrial restructuring that alter demands and increase pollutant loads; (3) land-use changes that disrupt habitats and reduce the self-purifying capacity of rivers, lakes, wetlands, and aquifers. These stresses also cease to be episodic stresses that a water system can never recuperate from on known time scales. Rather, they are altering the conditions of the baselines, augmenting the vulnerability of events of a compound, drought, heatwave, wildfire sequences, or flood pollution pulses, and revealing the constraints of the traditional management approaches that regard water quantity, water quality, and wildlife ecosystems as distinct issues. It is on this ground that the notion of water resources health has become a pragmatic conceptualization to diagnose system health and dictate interventions, due to its focus on functionality, systemic stability, and not one-problem compliance, or short-term sufficiency^[2].

Meanwhile, the world is going carbon neutral, and it is transforming how the concept of environmental management is applied. Carbon neutrality at the national, regional, or organizational level will involve the systematic decline of the quantity of greenhouse gases produced and, where needed, plausible improvement of removals or sinks. There are two ways in which water systems are closely linked to this transition. To begin with, water provision and water management are activities that are carbon-related. Abstraction, pumping, conveyance, and treatment energy can

be large, especially where water needs to be raised over a gradient of elevation, moved between basins, or created using energy-intensive processes like desalination. The collection and treatment of wastewater may be a source of greenhouse gases both directly, such as through biological processes (especially nitrous oxide and methane), and indirectly through electricity and chemical requirements. Second, the ways of decarbonization can transform water systems and watersheds. Implementation of renewable energy, electrification plans, onshore carbon capture and sequestration, and industrial processes are all effects that affect water requirements, water quality threats, and ecosystem character, and climate alleviation plans may either conflict with or support water aspirations based on design. It is a two-way courier that no longer can water health diagnosis and carbon-neutrality construction cannot be treated as two separate agendas; they are increasingly inseparable components of the same sustainability challenge^[3,4].

The real dilemma is that when actions are taken to enhance one aspect, others are neglected and need to be improved. An example is to use aggressive water reuse systems, which can decrease the amount of water withdrawn to the surface, and make the supply more reliable, but possibly at the expense of growing energy demand and the emissions produced by energy generation by powers-that-be, unless treatment needs are low, and sophisticated processes are implemented with clean electric power. On the other hand, decarbonization initiatives like electrification of pumping stations or the incorporation of renewables would help in lowering the intensity of emissions per cubic meter of delivered ecological flows, but they are unlikely to support the ecological flow need or load of pollution unless linked to basin health targets. Nature-based solutions, such as wetland restoration, riparian buffers, and soil conservation, are also said to be win-win solutions that would enhance water control, as well as carbon storage; however,

their net climate effect is additivity, permanence, and the possible offsetting emissions such as methane in the saturated environment. These complications help to reveal one of the main requirements: water resources health diagnosis should transform into a stand-alone evaluation process into an operational backbone of an environmental management system that will logically fit a carbon-neutrality goal, transparent accounting, and adaptive governance^[5,6].

In that regard, a health diagnosis means not just a compilation of indicators or ranking areas. It suggests the systematic process that (i) creates the boundaries and intended functions of systems, (ii) creates the baseline and identification of departure from healthy operation, (iii) attributes drivers and paths where feasible, (iv) evaluates risk and strength under realistic futures, and (v) supports decision-making on actions and priorities of monitoring. Water resource health is inherently multi-dimensional, and usually includes water quantity security, water quality condition, ecological integrity, service provision (e.g., reliable supply, flood control), and shock resilience. Fastening a diagnosis framework must consequently combine physical hydrology, biogeochemistry, ecology, and the socio-economic dependencies, yet it must take cognizance of the fact that data constraints and scale slugs usually limit what to measure directly. Carbon neutrality further complicates the situation; they require that emissions and removals be quantified in a manner that is comparable across studies and credible to be reported, and also avoids counts in both directions (i.e., the facility level inventories and the basin level land and water processes are consistent). The integration of water health and carbon goals, therefore, relies not solely on scientific models but also on the coherent measures, strong uncertainty management, and an institutional mechanism of check and improve that will learn with time^[7,8].

The environmental management systems (EMS) offer a day management system of organizing this integration in that they formalize the orientation between the assessment and action, verification, and continuous improvement. Applied to the water-carbon issue, an EMS view implies the cyclical management: conditions diagnosis; establishing goals within the framework of ecological boundaries and carbon limits; choosing the intervention portfolio; taking actions; controlling performance; and revising

the plans depending on the measured results and fresh intake of information. In a carbon-neutral building, the check element will need measurement, reporting, and verification of emissions reductions and removals, preferably, coupled with water health outcomes to ensure that co-benefits and trade-offs are apparent as opposed to presumed. Its opportunity core is to transform diagnosis into a management operating system, which integrates basin health objectives, infrastructure choices, and carbon accounting into a sound decision-making framework^[9].

This integration is becoming more and more possible, but not automatic, thanks to recent progress both in monitoring and in digital technology. Remote sensing offers uniform, wide-scale data regarding land cover, vegetation activities, surface water locations, and indicators of water quality conditions, whereas networked sensors deployed in situ or Internet-of-Things systems assist in tracking flows, pressures, and pollutant concentrations at higher frequencies. These streams can be combined using data assimilation methods, and hybrid models can be used to enhance the estimation of unobservable states. Machine learning has added the ability in pattern detection, forecasting, and the ability to identify anomalies; however, it has to be used in a way that is restrained by its interpretability, inter-regional transferability, and the possibility of confounding in non-stationary systems. Scenario analysis and causal reasoning still cannot be done without process-based models, but these have problems of calibration, parameter uncertainty, and computational burdens when applied to coupled water carbon ecosystem dynamics. A concept known as a digital twin, which is increasingly being used on infrastructure systems and environmental systems, provides a promising architecture to integrate real-time data, mechanistic knowledge, and scenario planning; however, it needs governance structures, interoperability standards, and practices of validation, which are currently under development in most areas^[10,11].

Despite growing interest, the literature has remained fragmented across disciplines that employ different terminologies, methods, and accounting boundaries. Water health assessment research often emphasizes indicator construction, integrated indices, and diagnostic ranking, but may treat energy use and emissions as externalities or omit credible MRV pathways. Carbon-neutrality research,

including net-zero planning and greenhouse gas invento-
 rying, often focuses on energy systems, industrial sectors,
 and land-based sinks, while simplifying hydrological con-
 straints and ecological thresholds or treating water impacts
 qualitatively. Meanwhile, practical environmental manage-
 ment is constrained by institutional fragmentation, where
 responsibilities for water supply, wastewater, watershed
 protection, land management, and climate policy are dis-

tributed across agencies with different mandates and data
 systems. These disconnections can lead to interventions
 that perform well in one domain but fail in another, or to
 planning that cannot be verified and improved because
 monitoring and reporting are not integrated with deci-
 sion-making. To formalize this integration, we summarize
 the diagnosis-to-management logic and its MRV require-
 ments within an EMS cycle (Figure 1) [12].

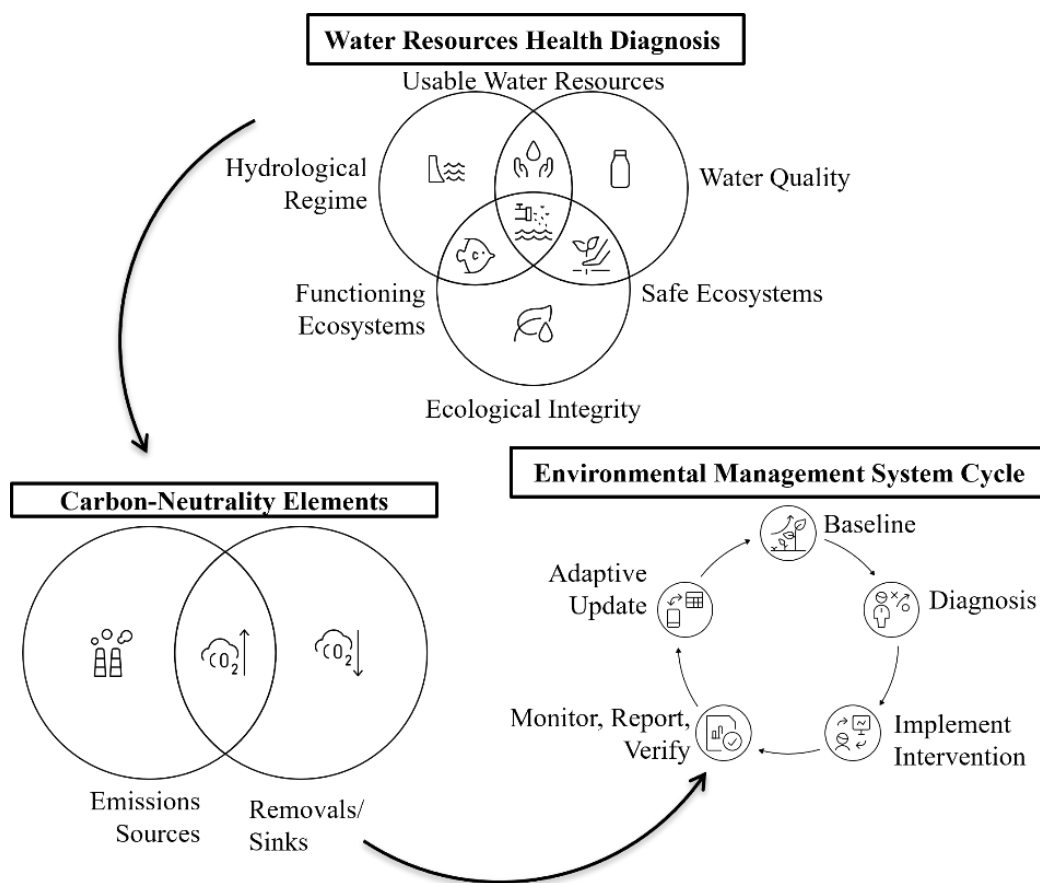


Figure 1. Conceptual framework linking water resources health diagnosis to a carbon-neutrality-oriented environmental management system.

This review is motivated by the need to synthesize
 these strands into a unified understanding of how water
 resources health diagnosis can be designed and operation-
 alized to support carbon-neutrality-oriented environmental
 management. The focus is not on promoting a single model
 or index, but on clarifying the methodological landscape,
 comparing strengths and limitations, and identifying the
 conditions under which different approaches are credible
 and useful. Particular attention is given to indicator sys-
 tems that can represent both water health and carbon-rel-
 ated performance in a compatible way, including energy and

emissions intensity metrics at facility and service levels
 and sink-related metrics at watershed levels [13]. Also dis-
 cussed in the review are diagnostic techniques, including
 multi-criteria decision analysis and composite indices, da-
 ta-driven methods, process-based models, and integrated
 system dynamics, with more focus on the validation prac-
 tices, quantification of uncertainty, and the resilience to
 deep uncertainty. Notably, the review relates diagnosis to
 action by categorizing intervention options into portfolios
 and explaining how they can be incorporated into an EMS
 direction that incorporates MRV on carbon outcomes and

water monitoring on health improvement.

This article becomes an effective contribution to the actual conceptual framework of integrated planning by compiling the evidence at different levels, such as the utility and treatment plants, all the way to the basins and regions. The starting point of such a framework is adequate boundary-setting: the target is operational carbon neutrality of a water utility, territorial carbon neutrality of an area that contains water-related emissions and sinks, or a basin-level approach that includes a decarbonization and ecological health balancing. Then it needs a small but strong set of central metrics, which is backed by a clear weighting and aggregation strategy in which composite indices are employed. Diagnosis should be accompanied by scenario analysis that expresses climate and socio-economic non-stationarity, and decision tools that not only can indicate trade-offs, but can also indicate them. Lastly, the loop of EMS needs to be closed by monitoring, MRV, and adaptive adjustment, and the recorded carbon benefits and water health outcomes should be both measurable and verifiable^[14].

The review also identifies persistent gaps that inhibit the implementation of synthesizing the state of knowledge. These are inconsistent definitions and standards of healthy water systems, little causation between interventions and observed outcomes, poor incorporation of greenhouse gas process emission (methane and nitrous oxide in particular) to water sector planning, and inadequate propagation of uncertainty upon integration of models of hydrology, water quality, ecology, and carbon accounting. Just as crucial are the issues of governance and equity: carbon-neutrality policies that increase the price of water, limit access, or relocate burdens to the vulnerable communities are unsustainable, whereas ecological goals disregarding livelihood requirements are unrealistic. The system of diagnosis and management should thus be integrated to provide a transparent trade-off analysis and include constraints that reflect ecological thresholds, affordability and distributive effects^[15].

Finally, the creation of carbon neutrality cannot be seen as a peripheral project of water management, nor can water health be degraded to a system of fixed indicators in a world that is rapidly evolving. A carbon-neutrality-oriented environmental management system coupled with

water resources health diagnosis is a transition to a more quantifiable, adaptable, and responsible governing of water-carbon-ecosystem interactions. The paragraphs that follow combine ideas and approaches and appraise indicators and diagnostic frameworks, and integrate intervention and digital-enabling pathways, to support not only scientific progress but also practical implementation in areas seeking to become carbon-neutral development and protect the health of their water systems.

2. Concepts, Definitions, and Review Methodology

2.1. Core Concepts and Working Definitions

Here, the term water resources health is employed as an integrative concept that defines the degree to which a water system can support critical human and ecosystem processes given the conditions prevailing and the disturbances that are likely to occur in the future^[2]. This framing takes into consideration a broader range of single-issue appraisals like sufficiency of water quantity or adherence to individual water quality criteria, but rather a more comprehensive way of functioning, on a multi-dimensional scale, such as hydrological regime stability, water quality integrity, ecological structure and function, service performance, and resilience to extreme events and long-term change. Health diagnosis, the process of identification of current status, identification of deviation of desirable or safe operating ranges, interpretation of probable drivers and mechanisms, and facilitation of the prioritization of management responses are termed as Health diagnosis. Detection is considered an action-oriented phase between observation and modelling for the design of interventions instead of a purely descriptive judgment.

Carbon neutrality construction is perceived as the creation of government schemes, technologies, and managerial routes that meet net-zero emissions of greenhouse gases within a specific scope and timeframe^[16]. This review distinguishes operational carbon neutrality on the level of water utilities or facilities and territorial carbon neutrality on the level of city, region, or basin, where land-based sinks and various sectors interact. Since boundaries determine both the interpretation and comparability, this review uses the level of water utilities or facilities as the

operational level, and city, region, or basin as the territorial level. Carbon-related outcomes are understood through the reduction of emissions and the increase of removals, and this area needs special attention. Credibility characteristics, including additionality, permanence, and leakage, can be poorly considered in the example of nature-based approaches in watersheds. Greenhouse gas is relevant in water-containing systems through the non-energy carbon dioxide emission involved in processes (especially methane and nitrous oxide) in the collection and treatment of wastewater, in sludges, and in aquatic or semi-aquatic ecosystems. The review thus considers carbon as a short-term in reference to multi-gas climate forcing in a common accounting unit, although acknowledging that underlying processes and uncertainties differ greatly between gases and environments.

The current definition of an environmental management system can be stated as a system of iterative and structured management where a diagnosis is transformed into measurable and verifiable action by means of planning, implementation, monitoring, and continuous improvement^[17]. By operating through the water health diagnosis concept, the EMS concept is applied to link carbon-neutrality targets with the concept of closed-loop management, where the indicators and models are not the end-products, but the input to the decision-making process, performance measurement, and correction. Measurement, reporting, and verification (MRV) is seen as a crucial part of the EMS, as in the absence of MRV, it is hard to tell what real improvements have actually taken place and which gains are apparent due to boundary redrawing, baselines shifting, and unverified assumptions about carbon sinks and evaded emissions.

2.2. Coupling Mechanisms and Boundary Setting in Water-Carbon Integration

Water health and carbon neutrality are coupled through multiple pathways that operate across scales. At infrastructure and utility scales, energy consumption for abstraction, pumping, conveyance, desalination, and treatment links water services directly to emissions intensity, while chemical and material inputs add embodied emissions that can be relevant where life-cycle perspectives are adopted. Wastewater systems introduce additional coupling

through biochemical processes that can generate methane and nitrous oxide, and through opportunities for energy recovery that reduce net emissions while potentially improving operational efficiency. At basin and landscape scales, land use and ecosystem interventions that influence infiltration, runoff generation, sediment transport, nutrient cycling, and habitat quality also alter carbon cycling, including soil organic carbon storage, biomass accumulation, and greenhouse gas fluxes from wetlands, floodplains, and reservoirs. Climate change heightens such couplings by adjusting hydrological regimes and water temperatures, changing biogeochemical reactions, changing ecosystem structure, and changing the incidence and intensity of extremes that can predominate in both physiological health products and emissions patterns^[17,18].

The concept of boundary setting is a fundamental keystone for these interdependencies to cohere. This review will use a boundary first lens where all diagnostic and management assertions are viewed in terms of a spatial boundary (facility, city, basin, region), a temporal boundary (period of operation, project life, restoration period), and also an accounting boundary (direct emissions, energy-related emissions, supply-chain emissions; emissions versus removals). The choice of the boundaries determines the selection of the indicators, the data requirements, and the validity of the cross-study comparisons. Because integrated conclusions are highly sensitive to system definition, we organize boundary choices across spatial, temporal, and accounting dimensions (**Figure 2**)^[19]. They also shape which trade-offs become visible. For example, improvements that reduce local withdrawals may impose external energy or emissions burdens if water is imported over long distances, while land-based sink projects may appear beneficial in carbon terms yet pose risks to water availability if they increase evapotranspiration or alter downstream flow regimes. Throughout the review, methods are therefore evaluated not only for technical sophistication but also for boundary coherence and their ability to represent cross-scale effects without creating misleading conclusions. To reduce ambiguity and improve comparability across disciplines, we consolidate working definitions and boundary choices used throughout this review (**Table 1**)^[20,21].

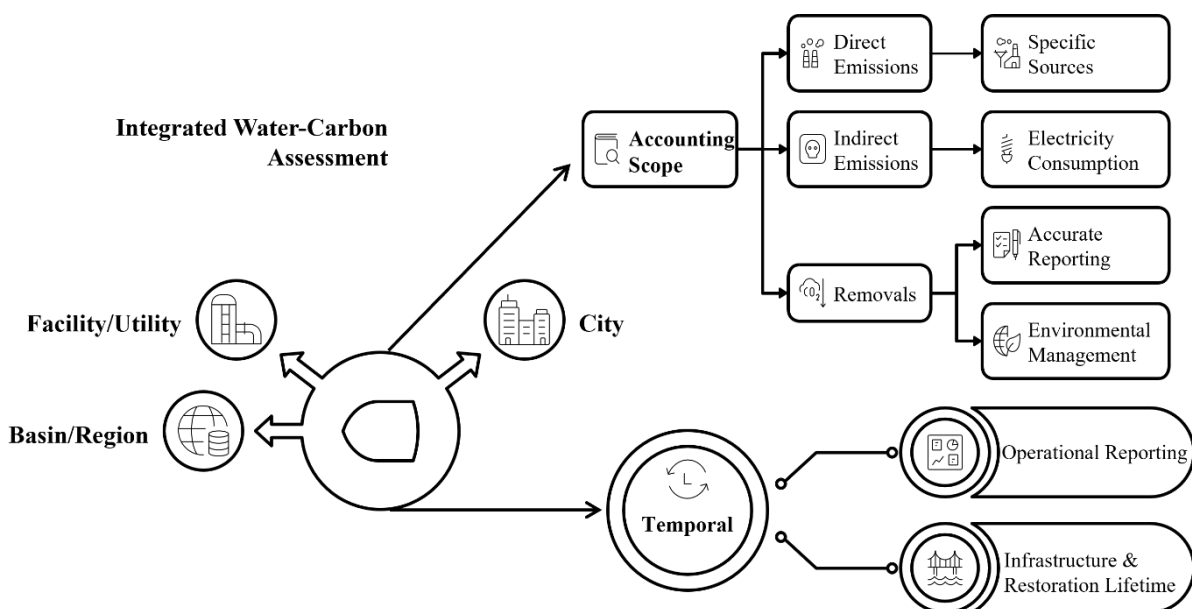


Figure 2. Boundary-setting schematic for integrated water-carbon assessment across scales.

Table 1. Concepts and boundary definitions for integrated water health-carbon neutrality research.

Term	Working Definition	Typical Boundary Choices	Common Pitfalls/Notes
Water resources health	Integrated ability of a water system to sustain hydrological function, water quality, ecological integrity, and service performance under disturbance	River reach, lake, aquifer, sub-basin, basin; sometimes utility service area	Over-reliance on single indicators; ignoring ecological thresholds and lag effects
Health diagnosis	Process of determining status, trend, and vulnerability, and translating results into actionable priorities	Snapshot vs time-series; operational vs. planning horizon	Treating diagnosis as ranking only, without driver attribution or uncertainty
Carbon neutrality	Net-zero greenhouse gas (GHG) emissions within a defined boundary and time horizon, via reductions and credible removals	Facility/utility, city, region, basin; operational vs. life-cycle	Boundary ambiguity, double counting, and confusing avoided emissions with removals
MRV	Measurement, reporting, and verification of emissions reductions/removals with traceability and auditability	Metering and inventories; models and monitoring plans	Weak verification for non-CO ₂ gases; uncertain removals treated as certain credits
Operational emissions	Emissions from on-site fuel use, purchased electricity, and relevant direct process emissions	Utility or facility (water supply/wastewater)	Omitting methane/N ₂ O in wastewater; inconsistent electricity emission factors
Removals/sinks	Net uptake and storage of carbon in biomass/soils/wetlands, etc., minus associated GHG fluxes	Watershed/landscape projects	Permanence/leakage risks; methane offsets in saturated systems
System boundary	Explicit definition of spatial, temporal, and accounting scope for diagnosis and reporting	Facility-basin; annual-lifecycle; direct-indirect	Incomparable results across studies due to inconsistent scopes

2.3. Literature Search Strategy and Source Selection

The review is designed as a structured synthesis of peer-reviewed research spanning water health assessment, integrated water resources management, water-energy-carbon nexus studies, carbon-neutrality planning, and environmental management systems^[22,23]. Searches are conducted using major bibliographic databases that provide

broad coverage of environmental science, engineering, and sustainability scholarship. The search logic combines terms capturing water system condition and diagnosis (including water resources health, watershed health, ecological health, water security, resilience assessment, and risk diagnosis) with terms representing carbon-neutrality objectives and management architectures (including carbon neutrality, net zero, greenhouse gas accounting, MRV, emissions intensity, life-cycle assessment, environmental

management system, decision support, and digital twin). Because terminology varies across disciplines and regions, the query structure is designed to include both conceptual keywords and methodological keywords to reduce the risk of omitting relevant work that is framed differently but methodologically aligned.

In order to achieve the relevance to the combined goal of this review, the search strategy lays emphasis on the studies that explicitly relate water evaluation to the consequences of carbon or present transferable techniques allowing one to make such a correlation. This encompasses papers that measure energy or emissions implications of water interventions, those papers that take into account a greenhouse gas module within water system models, and research that forms decision frameworks that can perform multi-objective optimization across water and carbon measures^[24]. Along with database searches, backward and forward citation tracking is employed to determine the underlying frameworks and seminal methodological contributions that just might not be found using only keyword searches, especially in older work where a particular set of terms is used to represent a similar concept.

2.4. Inclusion, Exclusion, and Screening Procedures

Eligibility criteria are defined to maintain a clear focus on diagnosis-to-management integration while still capturing methodological diversity. Included studies typically provide one or more of the following: a defined indicator system for water resources health with reproducible construction; a diagnostic method that evaluates water system condition, resilience, or risk; a quantified link between water interventions and carbon outcomes; or an EMS-like structure that operationalizes assessment into planning, implementation, and verification^[12,25–27]. Empirical case studies, methodological papers, and review articles are all eligible when they contribute substantially to one of these aims, with review articles used primarily to map established knowledge and identify methodological lineages rather than as sole evidence.

Studies are excluded when they address water quantity or water quality in isolation without an integrative diagnostic component, when they focus on carbon

neutrality without substantive water-system relevance, or when they present conceptual discussion without sufficient methodological detail to support synthesis^[21]. Screening is carried out in sequential stages beginning with titles and abstracts, followed by full-text review for uncertain cases. Disagreements in eligibility determination are resolved through re-examination against the inclusion logic, with preference given to retaining studies that introduce methods or evidence directly enabling integrated assessment, even if their original application context is narrower than the full scope of water health and carbon neutrality.

2.5. Quality Appraisal and Evidence Grading

Since the methods used in this discipline are diverse in nature, quality appraisal is modeled in terms of transparency, validity, and decision relevance, and not through a single methodological hierarchy. The appraisal focuses on the clarity of indicator definition and source of data, model structures, assumptions, calibration, as well as validation procedures of predictive or process-based models, and uncertainty, where possible, is considered and quantified. In the research into investigations that state the effectiveness of interventions, the plausibility of causal interpretation is considered, such as whether confounding variables are discussed, whether the baseline conditions and counterfactuals are specified. Specific attention is paid to carbon accounting, the concept of boundary clarity, the treatment of direct and indirect emissions, management of non-CO₂ gases, and the support of removals or sink claims by plausible logic of monitoring and verification^[28].

Instead of eliminating all the studies that have limitations, the appraisal is applied to place findings in synthesis. Categories in evidence interpretation are categorized: the evidence is considered as stronger when it is founded on measured evidence, strong validation, and clear uncertainty treatment, and the evidence is considered as weaker when the evidence is based on untested assumptions, unclear baselines, or incomplete accounting. This strategy facilitates a balanced review that guides the process of mapping the available practices and new approaches without being overconfident about the findings, which are not yet operationally reliable.

2.6. Data Extraction, Synthesis Framework, and Classification Scheme

Each of the eligible studies is standardized in extracting information in such a way that the information can be compared across various approaches. Elements extracted are the application name and scope, system boundary definition, the types and methods of indicators, source of data, and time span, the type of diagnostic or modeling technique, and any explicit carbon accounting or MRV element^[29]. In the case of the intervention analysis, the form of intervention, the measurement of the outcomes, and any trade-offs or limitations are noted. The structure of this extraction is that synthesis along two overlapping axes: the axis of diagnosis methods (indicator-based evaluation, multi-criteria decision analysis, data-driven modeling, process-based modeling, and integrated simulation) and the axis of management system design (how the results of diagnosis are converted to targets, intervention portfolios, monitoring plans, and iterative improvement).

The synthesis is carried out on the basis of thematic integration and comparative evaluation. Thematic integration finds patterns in conceptualizing and operationalizing water health, the introduction of carbon-related metrics into evaluation, and the construction of decision support^[30]. Comparative evaluation studies the suitability of methods in varied data regimes, scales, and contexts of decisions with interest in interpretability, robustness, transferability, and readiness to meet MRV. These two synthesis strategies are designed to generate an SCI-level review deliverable that is conceptually consistent and practically applicable: it helps to map out the methodological environment of the field and provides an organized framework on how to construct water health-carbon neutrality environmental management systems.

3. Indicator Systems for Water Resources Health and Carbon-Neutrality Linkage

3.1. Rationale for Integrated Indicator Design

The key interface between the complicated water-ecosystem processes and the decision of action is the indicator systems. They convert heterogeneous observa-

tions and model outputs into similar condition, trend, and risk representations, which allow diagnosis, communication, and prioritization. Within the framework of a carbon-neutral construction, the indicator systems should fulfill a new purpose: they should bring the carbon impacts of water management decisions into the perception, and vice versa^[31]. This involves going beyond parallel water indicators and carbon indicators to composite designs with parallel choices of boundaries, time, and aggregation scale. Otherwise, indicator systems can produce misleading signals, such as by rewarding interventions that can improve local water metrics at the cost of increased life-cycle emissions, or in which carbon benefits are realized through actions that impair ecological flows or water quality resilience.

A further requirement is that indicator systems support both diagnosis and management. Diagnostic indicators characterize current health status and the proximity to thresholds, while management indicators track performance, implementation progress, and verified outcomes (e.g., emission reductions, ecosystem recovery) under an EMS cycle^[32]. For Science Citation Index (SCI)-standard applicability, an indicator system should therefore be explicit about the intended decision use, specify the computation method and data provenance, and provide a pathway to update indicators as monitoring improves and conditions change. This is particularly important in non-stationary environments where climatic and socio-economic baselines shift, making static benchmarks progressively less informative.

3.2. Water Resources Health Indicator Architecture

Most water resources health frameworks converge on a multi-dimensional architecture, even when terminology differs. Hydrological regime indicators describe the adequacy, variability, and reliability of water quantity across surface water and groundwater domains. Typical representations include water availability relative to demand, flow duration characteristics, baseflow contributions, groundwater level trends, recharge-to-withdrawal balance, and the degree to which flow regulation alters seasonal patterns. Increasingly, environmental flow compliance is treated as a core health variable, because ecological integrity is highly sensitive to the magnitude, timing, duration, and fre-

quency of flows rather than to annual totals alone. Where floods and droughts dominate risk, hydrological extremes are represented through indicators capturing deficit severity, return periods, and multi-hazard exposure^[33].

Water quality indicators are commonly organized around pollutant categories and ecological response, spanning conventional parameters such as nutrients, organic pollution, suspended solids, salinity, and toxic contaminants, and in some settings extending to emerging contaminants^[34]. For integrative diagnosis, the key issue is not merely concentration exceedance but the load dynamics and the capacity of the system to dilute, transform, or retain pollutants under variable flows. Indicators that capture load per unit area, source contributions, or event-driven pulses can therefore be more diagnostic than static concentration metrics, especially in basins where episodic storm events drive disproportionate pollution and ecological damage.

Indicators of ecological conditions are structural and functional integrity of both aquatic and riparian systems^[35]. These are biological assemblage metrics, habitat quality and connectivity, riparian condition and proxies to ecosystem productivity. Direct ecological monitoring is often restricted in most areas, where indicators are based on habitat proxies using land cover data or geomorphology, with supplementation of biological censuses, which are done periodically. The scientific issue here is to strike a balance between ecological realism and data availability without ignoring the fact that the responses of the ecosystem in many cases have time lags and threshold behavior. This can, in turn, require that ecological indicators are framed in a resilience context in which the consideration does not just lie in the present state but the capacity of the system to continue functioning amidst disturbance.

Service and socio-economic indicators reflect the performance of water systems that are directly related to human beings, such as reliability of water supply, access, affordability, irrigation security, and flood control^[36]. Such indicators are necessary since the health of water resources is in part the ability to maintain service provision, but such indicators add value, condition, and distributional issues. A service indicator may show stable aggregate performance while masking inequities among communities or sectors. For this reason, many contemporary frameworks incorpo-

rate vulnerability and adaptive capacity metrics, linking exposure to water stressors with sensitivity and response capacity. In carbon-neutrality contexts, such metrics also help anticipate the equity implications of decarbonization measures that may alter costs or service levels.

3.3. Carbon-Related Indicators Embedded in Water Health Assessment

Linking carbon neutrality to water resources health requires indicators that represent greenhouse gas impacts in forms that can be compared and optimized alongside water metrics^[37]. At infrastructure and utility scales, the most widely transferable carbon-related indicators are energy intensity and emissions intensity. Energy intensity expresses the energy required per unit of water delivered or treated and can be disaggregated by process steps such as abstraction, pumping, treatment, distribution, collection, and effluent management. Emissions intensity extends this representation by incorporating the carbon content of electricity and fuels and, where possible, direct process emissions. For wastewater systems, process emissions indicators are particularly important because methane and nitrous oxide can dominate climate forcing even when electricity use is moderate. Consequently, a robust indicator system should, at a minimum, distinguish energy-related emissions from biological process emissions and clarify whether only operational emissions are included or whether embodied emissions from chemicals and materials are considered.

At basin and watershed scales, carbon indicators often relate to sink potential and landscape carbon dynamics^[38]. However, sink accounting is substantially more uncertain than operational accounting, especially in aquatic and semi-aquatic environments where methane emissions can offset carbon storage gains. For this reason, sink-related indicators require explicit treatment of uncertainty and verification readiness. In many applications, it is scientifically more defensible to report sink indicators as potential or scenario-dependent estimates rather than as definitive credits unless monitoring and verification mechanisms exist. Indicators may therefore be structured to reflect both gross sequestration potential and net climate impact, including plausible methane and nitrous oxide flux ranges, to avoid systematically biased conclusions.

A key integration objective is to construct nexus indicators that capture joint performance rather than separate outcomes. Examples include the water health improvement achieved per unit emissions reduced, or the emissions impact per unit pollutant removed. Such indicators support portfolio decision-making by identifying interventions that provide high co-benefits and flagging those with strong trade-offs. However, nexus indicators are sensitive to base-

line selection and system boundary assumptions; therefore, the indicator design must specify baselines and ensure temporal alignment between water outcomes, which may respond slowly, and emissions outcomes, which may change rapidly with operational adjustments. Based on the reviewed literature, we summarize an indicator architecture that jointly supports water health diagnosis and carbon-neutrality performance tracking across scales (**Table 2**)^[4,39].

Table 2. Recommended indicator system for water resources health diagnosis with carbon-neutrality linkage.

Dimension	Example Indicators (Illustrative)	Data Sources	Scale Suitability	Carbon-Neutrality Linkage
Hydrological regime	Environmental flow compliance; runoff variability; groundwater trend; water scarcity index	Gauges, groundwater wells, reanalysis, remote sensing	Reach-basin	Alters pumping/treatment needs; affects ecosystem resilience and restoration outcomes
Water quality	Nutrient loads: Total Nitrogen/Total Phosphorus (TN/TP); Biochemical Oxygen Demand/ Chemical Oxygen Demand (BOD/COD); salinity; metals; event-driven pollutant pulses	Monitoring stations, lab data, models	Reach-basin	Treatment intensity drives energy/chemicals; pollution control changes N ₂ O/CH ₄ risks in wastewater
Ecological integrity	Habitat connectivity; riparian condition; biodiversity proxy; ecological status class	Field surveys, habitat maps, Remote Sensing (RS) proxies	Reach-basin	Nature-based actions may increase sinks but also methane; ecological thresholds act as guardrails
Service performance	Supply reliability; non-revenue water; drought restriction frequency; flood regulation index	Utility data, hazard records	Utility-city	Efficiency improvements typically reduce energy/emissions per m ³
Resilience & risk	Vulnerability index; drought/flood compound risk; recovery time	Hazard models, socio-economic data	City-basin	Robust planning avoids emissions-intensive emergency supply and supports long-term adaptation
Energy intensity	kWh per m ³ abstracted/treated/distributed; kWh per kg pollutant removed	Supervisory Control and Data Acquisition (SCADA), energy meters	Facility-utility	Direct driver of operational emissions; key for decarbonization pathways
Emissions intensity	kgCO ₂ e per m ³ (by process); separate energy-related vs process emissions	Inventories, emission factors, direct measurements	Facility-utility	Enables tracking of net-zero progress; supports optimization and benchmarking
Sink/removal potential	Estimated net sequestration (with uncertainty); permanence risk indicator; methane risk flag	Field plots, RS biomass, flux studies/models	Basin-landscape	Must be reported with confidence bounds; avoid treating potential as verified removals

3.4. Normalization, Weighting, Aggregation, and Thresholding

Transforming multi-dimensional indicators into diagnostic outputs typically requires normalization and, in many cases, aggregation. Normalization methods vary from min–max scaling and z-score approaches to threshold-based scoring, where values are mapped to health grades relative to standards or ecological limits^[40]. The choice of normalization influences interpretability and comparability. Threshold-based scoring is practical for managers because it links directly to targets and compliance, but it depends on

defensible thresholds that may differ among ecosystems and social contexts. Statistical normalization facilitates cross-region comparisons but can obscure absolute risk when distributions differ across basins.

Weighting and aggregation are common in composite index construction, including approaches based on expert judgment, analytic hierarchy processes, entropy-based weights, principal component analysis, and Bayesian or hybrid schemes^[41]. The most important aspect of SCI-standard synthesis, rather than the general choice of what method to use, is that weighting decisions are transparent, sensitivity is tested, and the results are robust to plausi-

ble alternative weight sets. Composite indices provide the communicability and convenience of making decisions, but are susceptible to compensability issues in which the low performance in one of the crucial dimensions is vitiated by good performance in the others. The same can be addressed by non-compensatory aggregation or guardrail indicators, which are dimensions that need to pass minimum thresholds irrespective of composite score, especially where there is no compromise on ecological integrity or safe drinking water quality.

Diagnosis is especially critical with respect to thresholding and benchmarking^[42]. Health framing means that there are safe or desirable ranges of health, but in many cases, there are no universally applicable thresholds in water systems because of heterogeneity in the ecological setting and divergent social needs. Thus, more powerful indicator systems are becoming part of several layers of benchmarks that include regulatory standards, ecological flow requirements, and historical reference conditions, where meaningful and context-specific targets are set. In the context of climate change, past points of reference might cease to be desirable or achievable conditions; benchmarking frameworks need to adapt in an adaptive direction to reflect emerging risks and societal tastes, whilst remaining available to safeguard important ecological processes.

3.5. Data Foundations, Observability, and Integration across Sources

The credibility of the indicators is limited by the coverage of the data, measurement error, and how well the indicators can be observed directly. Existing monitoring networks tend to support hydrological and water quality indicators, but there are still gaps in terms of observing groundwater, small tributaries, and the dynamics of event pollution^[43]. Limitations in ecological indicators are often due to the few biological surveys and unsynchronized sampling methods, resulting in the use of a proxy like a riparian vegetation index, a measure of habitat fragmentation, or a productivity measure derived by remote sensing. Carbon indicators also add further difficulties: operational energy use can be quantified at the facility, but to convert energy consumption into emissions, current grid emission factors are required, and clarity on accounting conventions

is needed and process emissions are poorly measured and have to be estimated based on models or emission factors, which may not reflect local conditions.

Remote sensing and geospatial datasets have become essential to fill spatial gaps and provide consistent basin-scale coverage^[44]. They support indicators of land cover change, surface water dynamics, evapotranspiration, vegetation condition, and some water quality proxies in optically clear waters. However, remote sensing products vary in resolution, revisit frequency, and uncertainty, and their applicability depends on local conditions such as cloud cover, water turbidity, and land surface complexity. Consequently, integrated indicator systems benefit from data fusion approaches that combine satellite observations, in-situ measurements, and model outputs, ideally with quality control and uncertainty characterization. For an EMS aligned with carbon neutrality, data integration must also support MRV workflows, meaning that data provenance, update frequency, and auditability become part of indicator system design rather than afterthoughts. To make indicator systems implementable in practice, we summarize a data-to-indicator pipeline that supports both diagnosis and MRV-oriented reporting (**Figure 3**).

3.6. Comparability, Transferability, and Minimum Core Metric Sets

The inability to be comparatively undertaken through the use of inconsistent indicator definitions, varying spatial entities, and inconsistent weighting plans is a long-standing weakness of water health studies. This problem is intensified by the carbon-neutrality integration since the calculations of emissions and sink accounting do not follow similar guidelines across disciplines and institutions. To control this, there is a trend in the literature to turn to the worth of minimum core sets of metrics that are easy, measurable, and scalable, supplemented with context-sensitive indicators reflecting local priorities. Hydrological reliability measures, indicators of the important pollutants, an ecological integrity proxy, and at least one of the resilience or risk indicators are typical of such a core set^[45]. In carbon linkage, core measures are frequently energy intensity and operational emissions intensity, and optional extensions of these measures to process emissions and sink-related indicators are made where data allow. Transferability does not

just require the use of similar metrics but also requires the metrics to indicate the same thing in all situations. As an illustration, the intensity of emissions per cubic meter is not comparable in a case where one study has considered electricity-related emissions, whereas the other study has processed emissions and chemical inputs. On the same note, ecological indicators cannot be transferred easily outside of reference conditions and standardized sampling. Therefore, an SCI-standard indicator framework must expressly

indicate the scopes of accounting data, sources of data, procedures to compute them, and the range of uncertainty, and warn of naive comparisons where these factors are different^[46]. Once this transparency is attained, indicator systems can be a universal language between diagnosis, intervention assessment, and MRV in carbon-neutrality-based environmental management that will enable learning between basins and speed up the shift from individualized evaluation to operational decision systems.

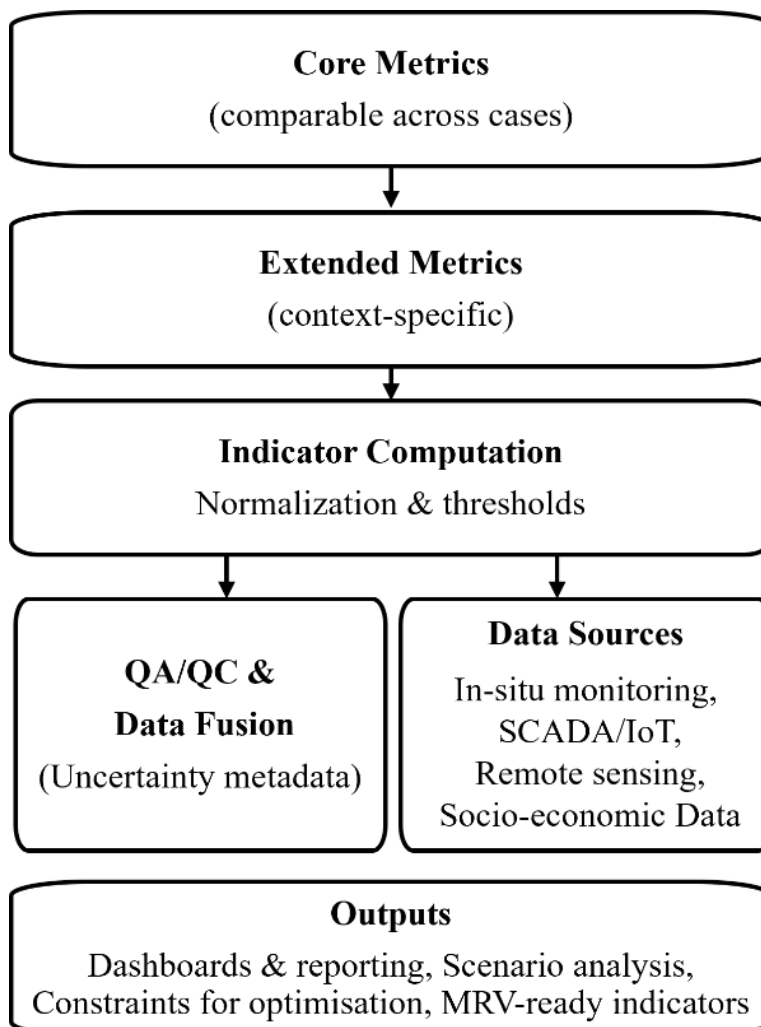


Figure 3. Indicator system architecture and data pipeline for water health and carbon linkage.

4. Methods for Water Resources Health Diagnosis

4.1. Role of Diagnostic Methods in an Integrated Water–Carbon Management Agenda

Water resources health diagnosis converts indicator

observations into viewable opinions regarding the state of the system, direction, and susceptibility, as well as offers a foundation for choosing and assessing management responses^[47]. Under the carbon-neutrality framework, diagnosis has to carry out two other tasks, which are usually not conducted during conventional water assessment. First, it should aid in decision-making within a set of multi-ob-

jective constraints, in which the ecological integrity and service reliability should be maintained, as well as emissions reduction and, where applicable, proven removals. Second, it has to operate in an iterative cycle of management which demands repeatable measurement, traceable assumptions, as well as the capability to revise conclusions as new data become available and as baselines shift due to climatic and socio-economic changes. As a result, the diagnostic approaches are evaluated in this review in terms of their capacity to rank/classify health, as well as their appropriateness as operational elements of an environmental management framework that combines monitoring, scenario planning, MRV, and adaptive intervention.

A further methodological requirement is explicit boundary coherence. Water health diagnosis can be performed at multiple scales, from a treatment plant or distribution district to a city and ultimately a river basin^[48]. Carbon-related outcomes similarly range from facility operational emissions to territorial accounting that includes land-based sinks and upstream supply chains. Diagnostic methods must therefore either accommodate scale coupling or clearly define the scope of inference. Methods that yield a single composite score can be useful for communication, but may become fragile when used for planning if the score mixes incommensurate processes or masks critical constraints. Methods that preserve dimension-specific information can be more actionable, particularly when used with optimization and scenario analysis, but require more careful interpretation and stakeholder engagement.

4.2. Composite Index and Multi-Criteria Diagnostic Approaches

Composite index approaches remain among the most widely used methods for diagnosing water resources health because they are conceptually accessible and can integrate diverse indicators into a single evaluative output^[47,49]. In a typical construction, indicators describing hydrology, water quality, ecology, and service performance are normalized, weighted, and aggregated to produce a health index that can be mapped spatially or tracked over time. Such indices provide an efficient means to identify hotspots and to communicate complex information to non-specialist decision-makers. They are also compatible with EMS reporting needs when computation procedures are standardized and

repeatable.

However, composite indices are methodologically sensitive to indicator selection, normalization, weighting, and aggregation rules^[50]. The most consequential issue is compensability, where poor performance in a critical dimension can be offset by better performance elsewhere, producing a “healthy” composite score despite unacceptable ecological or water quality risks. Non-compensatory aggregation rules or the use of constraint indicators can reduce this problem, but they require explicit articulation of which dimensions are non-negotiable and why. In carbon-linked applications, compensability becomes even more problematic because emissions reductions may not ethically or ecologically “compensate” for degraded environmental flows or drinking water safety, while sink gains may be uncertain or reversible. Therefore, index-based diagnosis is most defensible when coupled with guardrail thresholds and sensitivity analysis that demonstrates the stability of conclusions under plausible methodological choices.

Multi-criteria decision analysis (MCDA) methods generalize the index approach by structuring the diagnosis as a decision problem with explicit preference modeling. Methods such as analytic hierarchy processes, outranking approaches, and distance-to-ideal solutions are commonly used to evaluate water system health states or to compare management alternatives across multiple criteria. MCDA is particularly valuable when diagnosis is intended to support intervention selection because it can incorporate stakeholder priorities and highlight trade-offs among objectives. In integrated water–carbon applications, MCDA can include emissions intensity and carbon sink credibility as explicit criteria alongside water metrics, making the nexus dimension transparent^[21]. The key methodological challenge is that preference elicitation can introduce subjectivity and context dependence, and results may be sensitive to small changes in weights or scoring functions. Rigorous practice, therefore, requires transparent documentation of the preference model, stakeholder representation logic, and robustness testing.

4.3. Statistical and Machine-Learning-Based Diagnosis and Early Warning

The application of data-driven methods towards

water health diagnosis is growing, especially in cases of high-frequency monitoring or large spatial data sets (remote sensing). Multivariate sets of indicators, Statistical approaches, and machine learning are able to find patterns in multivariate indicators, detect anomalies, predict water quality or flow conditions, and estimate unobserved states (e.g., pollutant loads or ecological proxies) ^[51]. Such approaches can help process early warning of deviations of the expected work of the system, which is extremely important to avoid acute processes like algal blooms, contamination pulses, or ecological collapse caused by drought.

Three main ways in which data-driven methods can be applied in the diagnosis context are possible. The former is predictive diagnosis, whereby models are used to predict important health indicators at a given condition to give risk clues over a short period of time. The second is classification or clustering, where water bodies or sub-basins are classified into health states according to the similarity of indicators, and spatial prioritization becomes possible. The third is attribution-oriented analysis, in which the significance of the features or interpretable model forms is adopted that explains the possible causes of observed degradation, like the land-use intensity, hydro-meteorological anomalies, or infrastructure performance. To achieve carbon neutrality, data-based models can also predict energy consumption and emission intensity in other operational regimes, which aid in the assessment of operation strategies in a low-carbon mode ^[52].

Although these advantages exist, machine-learning-based diagnosis has some limitations, which are especially topical in coupled water-carbon systems ^[53]. Non-stationarity may cause model performance to become poorer; in this case, relationships estimated using past data are inaccurate because of changes in climate, policy, or technology. There is a common weakness in the transferability of models to space: a model developed in one basin can be ineffective in another with different hydrology, land cover, or management practices. In addition, most of the high-performing models are statistical correlators but not causal explainers, which restrains their utility in the design of interventions. Therefore, both data-driven prediction and mechanistic understanding and governance practices that deal with explainability, model drift, and uncertainty communication now tend to be viewed as a hybrid ap-

proach and the best practice. In the case of early warning systems, false positives and false negatives have varying costs, and therefore, there must be explicit calibration of the alert thresholds and decision protocols.

4.4. Process-Based Modeling for Hydrology, Water Quality, and Ecological Response

Physical, chemical, and biological Process-based models are models that are used to simulate the reaction of water systems to meteorological forcing, land-use change, and management interventions ^[54]. A runoff can be modeled as hydrological, routing, and groundwater can be modeled as hydrological, nutrient, and contaminant transport, and changes can be modeled as water quality, population, and ecological as biological condition. Process-based models in health diagnosis give a mechanism by which correlation can be transformed into explanation, so that scenario analysis can be used to assess the impacts that particular drivers or interventions have on water health outcomes. They are thus critical in carbon-neutrality-minded management in which the decision-makers need to evaluate the outcomes of infrastructure improvements, changes in operations, and watershed recovery conditions under realistic futures.

Constraints and thresholds can also be explicitly represented using process-based models. Constraints or response functions may be implemented to pinpoint the environmental flow requirements, pollutant load targets, and ecological regime shifts, and the diagnosis of current status, as well as something akin to proximity to critical transitions. In the case of carbon integration, process-based modeling may be extended to incorporate energy consumption modules of pumping and treatment of wastewater, and process emission modules of greenhouse emissions into wastewater. Carbon cycle representations can be coupled in the basin scale with land and water processes; however, the coupling introduces more uncertainty and data cost ^[55].

The principal limitations of process-based diagnosis stem from calibration and structural uncertainty. Many basins lack dense observations for groundwater, pollutant sources, or ecological conditions, making parameter estimation underdetermined. Different model structures can produce similar fits to historical data yet diverge under scenario conditions, a problem that becomes acute under climate change and land-use transitions. Computation-

al demands can also restrict the number of scenarios and uncertainty realizations that can be explored. Therefore, the credibility of process-based diagnosis depends on transparent reporting of calibration procedures, validation against independent data, explicit treatment of uncertainty, and careful matching between model complexity and data availability [56,57].

4.5. System Dynamics and Integrated Simulation for Coupled Water–Carbon–Society Systems

While process-based models emphasize biophysical mechanisms, system dynamics and other integrated simulation approaches are often used to represent feedback-rich interactions among water demand, infrastructure development, policy responses, economic drivers, and environmental constraints. These approaches are valuable when diagnosis is intended to support long-term planning rather than short-term forecasting, particularly in regions where demand growth, industrial transformation, or land management policy is central to water health outcomes. System dynamics models can represent stocks and flows of water storage, pollutant accumulation, infrastructure capacity, and adoption of technologies, linking them through feedback loops such as scarcity-driven conservation or pollution-driven regulation. We therefore classify diagnostic methods by how they support distinct functions within

an EMS cycle, from screening and forecasting to scenario evaluation and adaptive updating (Figure 4) [58].

In carbon-neutrality contexts, integrated simulation is especially relevant because decarbonization pathways often involve systemic transitions that alter both water and carbon dynamics [22]. As an illustration, the operational emissions can be reduced through electrification and integration of renewable sources, the peak electricity requirements in pumping can be changed, the resources of wastewater can be recovered by substituting the treatment plants with energy-producing ones, and the watershed restoration can cause a shift in hydrological control and carbon storage, as well as greenhouse gas flux. System dynamics frameworks then have the potential to facilitate the relationship between biophysical diagnosis and governance-based planning, allowing the exploration of levers associated with policy, timing of investment, and dependencies in pathways.

The trade-off of this is that integrated simulation may be based on simplified process relationships and aggregated representations. This may decrease the predictive skill of certain hydrological or water quality results, and may be destructive to parameterization lacking a robust empirical foundation. The integrated simulation is, therefore, best defensible in case of comparative scenario reasoning and not exact prediction, and it needs to be attached to empirical data and, where possible, to process-based sub-models of parts of significant concern [59].

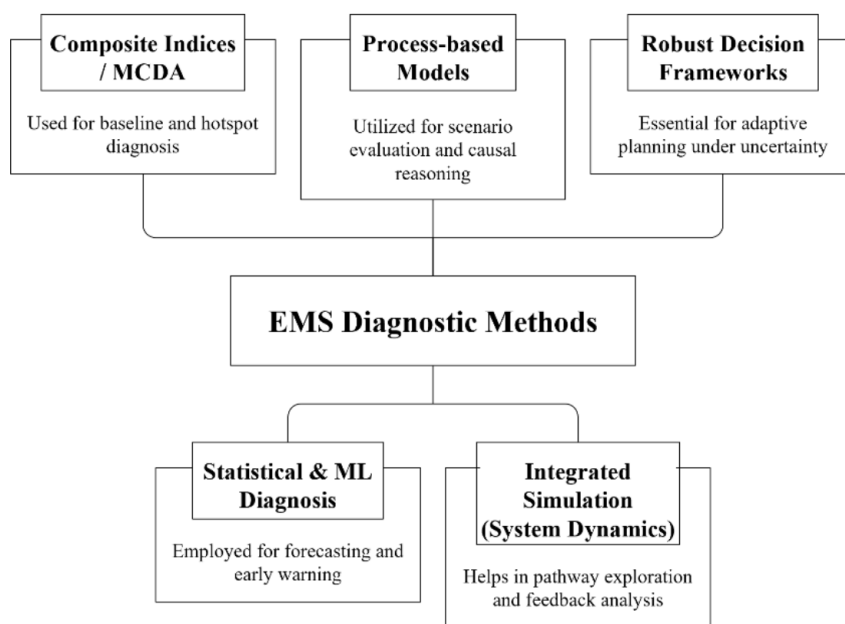


Figure 4. Taxonomy of diagnostic methods and their roles in the EMS cycle.

4.6. Validation, Uncertainty Quantification, and Robust Diagnosis under Deep Uncertainty

Across diagnostic methods, the reliability of conclusions depends on how uncertainty is handled and how models and indices are validated. Uncertainty arises from measurement errors, sparse monitoring, imperfect proxies, parameter estimation limits, structural choices in models, and scenario uncertainty related to climate, socio-economic development, and policy trajectories. In coupled water-carbon systems, uncertainty is compounded by boundary definitions, emissions factors, and the credibility of sink estimates, particularly for nature-based interventions where permanence and methane or nitrous oxide offsets are difficult to quantify^[60,61].

Validation practices differ by method. Composite indices require validation through consistency checks, sensitivity analysis to weights and normalization, and external comparison to observed ecological or service outcomes where possible. Data-driven models require train-test separation, cross-validation, and careful evaluation under distribution shifts to assess non-stationarity risk. Process-based models require calibration against observed flows and water quality, validation on independent periods or sites, and diagnostic checks on internal process realism. For intervention claims, validation extends to causal inference considerations: whether observed improvements can

reasonably be attributed to the intervention rather than to climate variability or concurrent policy changes^[62].

Due to the necessity to make many management decisions in spite of the strong uncertainty, a strong diagnosis has become a significant methodological direction. Strong methods focus on the decisions and interpretations that work well over a broad repertoire of plausible futures instead of being optimal towards any one forecast. In diagnosis, this is translated into the ability to recognize health vulnerabilities that are consistent across scenario ensembles, pointing to indicators that are always on the threshold, and also focusing on interventions that result in co-benefits or less risk across a variety of conditions. For carbon-neutrality construction, robust diagnosis is also tied to MRV readiness: emissions reductions and removals should be treated as reliable only to the extent that they can be measured, verified, and maintained over time^[29]. Embedding uncertainty-aware diagnosis into an EMS cycle allows iterative learning, where model structures and indicators are updated as monitoring improves, thereby progressively reducing uncertainty and increasing the effectiveness of integrated water health and carbon-neutral management. To support method selection aligned with decision purpose and data availability, we compare major diagnostic method families and their EMS/MRV readiness (Table 3).

Table 3. Comparison of diagnostic methods for water resources health (and readiness for carbon-integrated EMS use).

Method Family	Typical Outputs	Strengths	Limitations	Best Use Cases	EMS/MRV Readiness
Composite indices	Single score and sub-scores; maps; trend lines	Communicable; fast screening; supports reporting	Sensitive to weights/normalization compensability can hide critical failures	Baseline diagnosis, hotspot identification	Medium: strong if guardrails and sensitivity analysis are included
Multi-Criteria Decision Analysis (MCDA): Analytic Hierarchy Process (AHP)/Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)/ViseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR), etc.	Ranked alternatives; trade-off surfaces	Explicit trade-offs can include stakeholder preferences	Subjectivity, preference instability, requires careful documentation	Portfolio selection, multi-objective planning	Medium-High: good if preference model and constraints are transparent
Statistical/Machine Learning (ML) forecasting	Short-term predictions; anomaly alerts	Early warning; can use high-frequency data; scalable	Transferability and non-stationarity; limited causal insight	Operational control, risk alerts	Medium: strong for Check step if drift monitoring is implemented
Process-based models	Scenario impacts; load/flow responses; threshold proximity	Mechanistic explanation; scenario testing	Calibration demands, structural uncertainty, and computation	Policy evaluation, intervention design	High: supports Plan step when uncertainty is quantified

Table 3. Cont.

Method Family	Typical Outputs	Strengths	Limitations	Best Use Cases	EMS/MRV Readiness
System dynamics/integrated simulation	Pathways over time; feedback effects	Captures socio-technical transitions; long-horizon planning	Aggregation can reduce physical realism	Net-zero pathways, investment timing	Medium: suitable for strategy; requires grounding in data
Robust decision approaches	Strategies resilient across scenarios	Handles deep uncertainty; reduces overfitting to a single future	Needs scenario design; communication complexity	Climate non-stationarity, high-stakes planning	High: aligns with adaptive EMS cycles and uncertainty-aware reporting

5. Carbon-Neutrality-Oriented Environmental Management System and Digital Enablement

5.1. From Diagnosis to Closed-Loop Management under Carbon-Neutrality Constraints

An environmental management system oriented toward carbon neutrality differs from conventional water environmental management primarily in the way it formalizes targets, accountability, and verification [39]. Traditional water management has often relied on periodic assessments and project-based interventions, where success is inferred from improved indicator values or compliance outcomes. Conversely, carbon-neutrality construction demands a clear baseline, a clear boundary of accounting, a clear path of interventions, and a logic of monitoring and verification that can illustrate improvement over time. With these requirements coupled with water resources health diagnosis, the management system is a closed-loop process where the diagnostic output determines intervention choice, intervention is applied with specified performance measures, and monitoring results are returned to revised diagnosis and further planning. Diagnosis in such a loop is not a snapshot situation-at-a-time report of the state of the environment but a repetitive means of operation that keeps situational awareness and decision support as things change.

One of the main aspects of the carbon-neutrality-oriented EMS is that it focuses on the coherence of scales and actors. The scale of water health outcomes is often set at the basin level, and most decisions that are made in relation to carbon emissions are made at a facility or infrastructure level, including pumps, treatment trains, and

aeration operations [63]. A workable EMS, therefore, requires mechanisms to connect facility-level performance to basin-level health objectives, so that local optimizations do not create unintended downstream or cross-sector impacts. This connection depends on consistent indicator definitions, aligned temporal reporting windows, and explicit representation of constraints such as environmental flow requirements or pollutant load limits that cannot be traded away for carbon gains. The resulting system is best understood as an integrated governance and analytics architecture rather than as a single model, because it must coordinate monitoring, accounting, decision processes, and reporting while remaining adaptable to policy changes and technological evolution.

5.2. Baselines, Targets, and Performance Metrics for Integrated Water–Carbon Governance

An essential condition of the combination of water resources health diagnosis and carbon-neutrality strategies is baseline definition, but the two fields are based on radically different concepts of the baseline. Water health baselines normally come through ecological or historical reference conditions, including pre-disturbance ecological regime, ecological integrity indicators, or legislative water quality and ecological flow indicators. These baselines are desirable or threshold levels of ecosystems that are compared with degradation or recovery. They are normative and ecosystem-oriented in nature and, therefore, focus on resilience, supporting biodiversity, and long-term system functionality [64].

Conversely, carbon baselines are usually placed based on greenhouse gas (GHG) inventories that measure emissions as a result of water-related infrastructure and

operations, such as the treatment process, pumping, and energy usage. These baselines indicate current levels of operation of emissions on a defined accounting boundary, and they are mainly utilized in determining the reductions of the emissions over a given time. The disparity between the carbon baseline and the condition of the ecological target is thus an accounting, not an ecological objective.

There are a number of methodological challenges to integrating these types of baselines. First, there is a conceptual asymmetry between ecological reference states and emissions inventories, and unified performance targets are hard to create. Second, scale mismatches are frequently seen: watershed-based water health assessment is usually carried out, but carbon accounts are usually accumulated at the facility or utility scale. Third, the common uncertainty in the estimation of emissions, especially of wastewater processes and nature-based interventions, makes the simultaneous assessment of water and carbon results difficult.

To this end, the integrated environmental management frameworks must explicitly harmonize these disparities by making spatial limits, time frames, and accounting assumptions coincide. In the absence of such alignment, a potential baseline there can play a role in the obscuration of trade-offs and overstatement of benefits of mitigation or invalidation of water carbon co-management strategies^[65].

5.3. Intervention Portfolio Design and Water–Carbon Trade-Off Management

Diagnosis should be translated into intervention portfolios instead of individual projects by the EMS since water health and carbon results are influenced by interactive actions among measures of demand, supply, treatment, and watershed processes. The demand side remedies like leakage control, pressure management, smart metering, and conservation have the potential to cut back the abstraction requirement and the pumping energy, and can provide both water and carbon advantages. The size and dispersion of benefits, however, are determined by local hydraulic conditions and user behavior, and conservation policies need to be developed keeping in mind the equity and service standards. Supply-side efforts like diversification of sources, inter-basin transfers, desalination, and expansion of storage can enhance reliability, with often serious energy and emission consequences. These choices, in carbon-neu-

trality building, need a frank assessment of different intensities of emissions under various mixes of electricity and varying working regimes, and ecological and social impacts at both source and reception basins^[22,66].

The key element of a carbon-neutral approach to water is the wastewater and sludge management interventions since they provide direct prospects of emissions reduction and alternative resources recovery routes^[67]. Net emissions can be reduced by means of process optimization, aeration control, anaerobic digestion, biogas utilization, nutrient recovery, and enhanced operations. However, the climate advantage will be based on the ability to regulate the release of methane and formation of nitrous oxide, which is very sensitive to process conditions and may not always be represented in standard inventories. Water control, mitigation of pollutant loads, and possible increase in carbon storage could be ameliorated through watershed and ecosystem interventions such as riparian restoration, the creation of wetlands, soil conservation, and green stormwater infrastructure. Their incorporation into the EMS must be done meticulously, considering the net climate impacts, especially where the emission of methane or permanent risks are significant, and the clear meaning of hydrological alterations in water flows and water availability in the downstream.

Because trade-offs are unavoidable in many settings, portfolio design increasingly employs multi-objective decision frameworks that identify solutions offering acceptable performance across water health, cost, and carbon constraints^[68]. The EMS perspective helps operationalize such frameworks by making trade-offs explicit and by defining how decisions will be revisited as monitoring reveals real-world performance. Importantly, trade-off management must also consider distributional outcomes, since the burdens of cost increases, land-use changes, or altered service levels may fall disproportionately on specific communities or sectors. An SCI-standard EMS design, therefore, treats equity not as an external policy add-on but as a constraint and performance dimension embedded in portfolio evaluation.

5.4. Carbon Accounting and MRV as an Operational Layer of the EMS

Measurement, reporting, and verification are the

mechanisms that convert carbon-neutrality commitments from aspirational statements into accountable progress. In an integrated water-carbon EMS, MRV must be designed to align with water health monitoring so that claims of co-benefits can be substantiated and so that trade-offs are detected early ^[69]. At the facility level, MRV typically begins with energy metering, process monitoring, and standardized emissions factor application for electricity and fuels. For wastewater systems, credible MRV requires additional attention to process emissions, which may require direct measurement campaigns, improved emission factor selection, or model-based estimation validated against observations. When chemical use is substantial, or when infrastructure construction dominates emissions, life-cycle perspectives may be necessary to avoid shifting emissions upstream without recognizing them.

For nature-based interventions in watersheds, MRV is more challenging because removals depend on ecological processes, vary spatially, and can be reversed by dis-

turbance or management change. An EMS that includes such interventions must therefore operationalize credibility criteria, including additionality, permanence, leakage control, and uncertainty quantification. Rather than treating sink estimates as fixed credits, integrated MRV increasingly represents them as ranges with confidence levels and uses monitoring plans designed to improve certainty over time. This approach is consistent with adaptive management: as monitoring improves, uncertainty narrows, and the EMS can make stronger claims or adjust strategies if expected removals do not materialize. Importantly, MRV also needs governance safeguards to prevent double-counting of removals across overlapping projects or jurisdictions, a risk that increases when water and carbon initiatives are managed by different agencies ^[70]. We present common intervention categories and summarize their water-carbon implications together with minimum MRV requirements to support portfolio-based EMS implementation (**Table 4**).

Table 4. Intervention portfolio options with expected water-health effects, carbon impacts, and MRV requirements.

Intervention Type	Primary Water-Health Benefits	Potential Carbon Effects	Key Trade-Offs/Risks	MRV Essentials (Minimum)	Digital Enablers
Leakage control & pressure management	Reduced withdrawals; improved reliability	Lower pumping energy and emissions	Rebound demand if not paired with demand governance	Water balance; energy metering; emissions factor tracking	Smart meters; Supervisory Control and Data Acquisition (SCADA); anomaly detection
Pumping/treatment electrification and renewables	Stable service with lower operational emissions	Strong emissions reduction if electricity is decarbonized;	Grid factor variability; capital costs	Electricity data; location-based/market-based factors; audit trail	Energy management systems; optimization
Advanced water reuse	Drought resilience; reduced abstraction	Can increase energy; may reduce upstream impacts	Concentrate brine/residuals; public acceptance	kWh/m ³ ; emissions intensity; effluent quality; uptime	Digital control; quality sensors; forecasting
Wastewater process optimization	Improved effluent; operational stability	Can reduce N ₂ O/CH ₄ and energy	Poor control can increase non-CO ₂ emissions	Direct/indirect process emissions estimation; periodic measurement	Online Dissolved Oxygen (DO)/Nitrogen (N) sensors; control algorithms
Anaerobic digestion & biogas utilization	Resource recovery; sludge stabilization	Potential net-zero/negative operations	Methane leakage; utilization efficiency	Biogas volume/composition; leakage checks; energy offsets	Gas monitoring; asset management
Nature-based restoration (wetlands/riparian)	Load reduction; habitat recovery; flood buffering	Potential removals; may increase methane	Permanence/leakage; land-use conflict	Baseline + monitoring plan; uncertainty bounds; methane risk screening	Remote sensing; field plots; Geographic Information System (GIS) tracking
Agricultural nutrient & irrigation optimization	Reduced diffuse pollution; water savings	Reduced N ₂ O via nutrient efficiency; energy savings	Adoption barriers; monitoring difficulty	Practice adoption verification; modeled load changes; uncertainty	Farm Internet of Things (IoT); Remote Sensing (RS); Evapotranspiration (ET); decision tools
Green stormwater/Low-Impact Development (LID)	Reduced runoff peaks; improved water quality	Embodied carbon varies; long-term co-benefits	Maintenance burden; performance variability	Asset inventory; performance monitoring; lifecycle boundaries	Sensors; digital asset logs; rainfall-runoff models

5.5. Digital Monitoring, Analytics, and Decision-Support Architecture

Digital enablement is a practical necessity for implementing a carbon-neutrality-oriented EMS at scale because the system requires frequent updating, cross-domain data integration, and traceable reporting. Monitoring architectures increasingly combine in-situ sensors, supervisory control and data acquisition systems in utilities, and remote sensing for basin-scale variables such as land cover, surface water dynamics, vegetation condition, and evapotranspiration. Data integration involves harmonizing temporal resolution, spatial referencing, and quality control, and increasingly relies on automated pipelines that can flag sensor faults, identify outliers, and propagate uncertainty metadata. In carbon-neutrality applications, integration must also link operational data to emissions calculations through consistent emissions factors and accounting rules, and must maintain auditability so that reported progress can be verified ^[71].

Analytics and decision support are in the spectrum between descriptive dashboards that show trends in indicators and predictive tools that estimate which risks will happen soon, and prescriptive tools that suggest changes in operations or investment portfolios. Multi-objective optimization may be especially useful in terms of balancing water health, cost, and carbon constraints, but it can only be effective in terms of the representations of the constraints and uncertainties. It is also necessary that scenario analysis be performed since the climate environment and policy environment are dynamic, and the value of interventions may change in alternative futures. Tools of this kind are most effective in an EMS when they are built into governance practices, e.g., periodic review cycles in which updated diagnosis and MRV findings are changed into new operation rules, investment priorities, or restoration plans. Such institutional embedding can be more decisive in effect than the fineness of the algorithms being used ^[72].

5.6. Digital Twins and Platformized EMS Implementation

The concepts of digital twin offer a coherent framework of combining monitoring data, models and decision processes in an EMS. Within the water-carbon framework,

a digital twin may be viewed as a dynamic model of the state and possibly a system, which is constantly updated with both operational and environmental data, and which can be utilized to simulate scenarios, assess interventions, and assist in real-time or near-real-time management. A facility-centred twin can be connected with hydraulics, energy consumption, and process emissions towards the water or wastewater treatment; thus, the operational strategy can be used to minimize emissions without the loss of compliance. A basin-centric twin can combine hydrological, pollutant transportation, ecosystem proxy, and land-management impacts, enabling the evaluation of the impact of restoration or land-use alteration on water health and carbon cycles ^[73].

Such twins must be implemented in a policy-relevant, SCI-standard manner that cannot be done just by software integration. It demands model governance practices such as version control, assumption documentation, calibration and validation practices, and model drift management procedures when conditions vary. It also needs interoperability standards to enable aggregating data between various agencies and platforms without data being lost, cybersecurity, and data-ethics protection, since the data of operational water infrastructure can be sensitive. Under these requirements, platformized EMS can offer a feasible path to scaling integrated water health and carbon-neutrality management to allow a uniform diagnostic, transparent MRV, and adaptive decision-making. The digital enablement has no overall value other than enhancing evidence-based governance: making visible the status of systems, explicit trade-offs, and progress determinable as regions strive to achieve carbon neutrality and protect the well-being of water resources ^[39,74].

6. Synthesis and Future Research Agenda

6.1. An Integrated Synthesis: Aligning Water Health Diagnosis with Carbon-Neutrality Construction

Across the reviewed literature, a consistent theme is that water resources health diagnosis and carbon-neutrality construction have matured largely in parallel, with only partial integration in methods, metrics, and governance

routines. Water health studies often emphasize comprehensive indicator design and basin-scale interpretation, while carbon-neutrality work tends to concentrate on emissions inventories, technology transitions, and net-zero pathways at organizational or territorial scales. Where integration exists, it frequently takes the form of adding energy intensity or operational carbon metrics to water-sector performance, or treating nature-based watershed projects as carbon sinks without fully embedding them into a water health diagnostic logic. This partial coupling is insufficient for decision-making because the most consequential outcomes arise from feedbacks and trade-offs, including energy–water dependencies in supply and treatment, process emissions in wastewater management, and hydrological impacts of land-based mitigation actions. A synthesis of current evidence therefore points to the need for a unified “diagnosis-to-management” architecture in which water health and carbon are treated as equally prioritized and jointly constrained objectives within a single system boundary and a single adaptive decision cycle^[22,39].

This synthesis can be expressed as a functional chain: boundary setting defines what the system includes and what success means; indicator systems translate the system into measurable states and performance dimensions; diagnostic methods interpret these measurements under uncertainty and generate actionable insights; and an EMS implements intervention portfolios with MRV to demonstrate progress and enable learning. The literature suggests that the effectiveness of any individual component depends strongly on its compatibility with the others. For instance, sophisticated process models cannot support management if indicators used for reporting do not reflect the modeled constraints, and high-frequency monitoring does not improve governance if it is not linked to decision routines and accountability structures^[75]. Integration is therefore not simply a matter of adding more indicators or building larger models; it is an alignment problem across definitions, scales, data pipelines, and institutional processes.

6.2. A Consolidated Framework for Integrated Assessment and Management

An integrated framework that comes out of the literature starts with the expression of a clear boundary choice in three dimensions^[76]. The spatial boundary is necessary

to indicate whether the system is a facility, a service area, a city, or a basin, and should explicitly deal with upstream and downstream connections that can move the impacts. Both the operational reporting period and the extended horizon within which ecological recovery or infrastructure changes are likely to be attained should be defined by the temporal boundary. The accounting boundary should also explain the categories of emissions to be incorporated and the way removals are treated, especially in cases where nature-based remedies are purported to be a part of neutrality. The indicators and diagnostic methods may be chosen and parameterized coherently when the boundaries are predetermined.

In this context, indicators are most applicable when they are arranged in a stacked arrangement. A basic layer has a minimum of sturdy, quantifiable measurements to attempt comparability across basins and programs, where an extension layer reflects local priorities and ecological particularity. Diagnosis goes on to adopt a hybrid approach, which couples method type to decision purpose: index or MCDA methods are useful in communication and prioritization, data-driven models are useful in forecasting and anomaly detection, and process-based models are useful in scenario analysis and causal reasoning about interventions. The EMS implements the framework by connecting the outputs of the diagnoses with the target setting, portfolio selection, and MRV, and specifying how often the assessments are updated and how the decisions are corrected. Integration in such a structure is realized not through coercing all the decisions on a composite score, but through traceability of raw measures to diagnostic conclusion, to management act, and confirmed results^[14,77].

6.3. Toward a Minimum Core Metric Set and Standard Reporting Logic

The literature indicates that lack of comparability and inconsistent accounting are among the most persistent barriers to cumulative knowledge building and scalable implementation. A pragmatic response is the development of a minimum core metric set that can be reported across contexts and updated through time, accompanied by standardized metadata that specifies data sources, computation methods, and uncertainty ranges. For water resources health, the strongest candidates for core metrics are those

that capture non-substitutable functions and constraints, including environmental flow compliance or a flow regime integrity proxy, a small set of key pollutant indicators expressed in ways that reflect loads and event sensitivity, and at least one ecological integrity proxy that is observable or defensible through proxy-validation chains. A resilience or risk metric is also important to reflect non-stationarity and the increasing dominance of extremes ^[78].

For carbon linkage, the most transferable core metrics include energy intensity and operational emissions intensity of water supply and wastewater services, expressed with explicit boundaries and updated emissions factors ^[65,79]. Where wastewater systems are significant, a core metric that represents process emissions, even if initially estimated with conservative factors, is important to avoid systematically undercounting climate impacts. For sink-related actions, the literature supports reporting potential removals separately from verified removals, with uncertainty and permanence explicitly represented. Standard reporting logic should avoid treating uncertain sink estimates as equivalent to measured emissions reductions, and should clearly distinguish avoided emissions from removals to prevent double-counting. The adoption of standardized core metrics does not replace local specificity; rather, it provides a stable backbone that enables learning across studies and supports auditability in carbon-neutrality-oriented management.

6.4. Methodological Gaps: Causality, Scale Coupling, and Uncertainty Propagation

Causal attribution is a major scientific deficit. It is possible to show correlations between the land use, variables of infrastructure, and health indicators in many studies, but it is not possible to attribute with strength changes in water health or emissions to specific interventions, particularly in the face of the variations in climate and changes in policies at the same time ^[80]. This constrains the trust of what works and makes it difficult to manage adaptively. To advance causal inference in this area, it is probable that a combination of quasi-experimental designs, wherever possible, long-term follow-ups that could identify pre- and post-intervention baselines, and the combination of mechanistic models with data-driven approaches is needed to isolate signal and noise. Attribution is also a challenge in the

carbon context due to varying grid emission factors and changing accounting regulations, which may give the false appearance of improvement in operations without any actual change, where such is not well managed.

Another gap that is still persistent is scale coupling. The decisions made at the facility level are capable of achieving quantified emissions, yet basin health outcomes are reliant on the processes and ecological reactions that are distributed across space and extended horizons. On the other hand, larger-scale restoration has the potential to enhance resilience and provide carbon benefits, but it is common that utilities and agencies do not have systems to implement the benefits into operational targets and budgets. To close this gap, diagnostic methods and indicator systems are needed that may capture cross-scale effects in a homogeneous manner and governance systems that may coordinate incentives among actors. According to the literature, digital twin architectures and comprehensive modeling environments have potential technical avenues, but their practical use requires validation, interoperability, and institutional acceptance ^[81,82].

The propagation of uncertainty is highly difficult when systems are coupled. The uncertainty may be large when hydrological models are inputted into water quality models, which in turn are used to denote ecological proxies, and are interoperated with emissions accounting and sink estimation. Composite outputs may easily conceal the resulting uncertainty ^[59,83]. However, when we are making decisions in the future that are carbon neutral, we need confidence limits, sensitivity drivers, and robustness understanding, but not a single deterministic figure. A significant research agenda is the creation of uncertainty-sensitive diagnostic processes that propagate uncertainty in data to models to end decision metrics, and which model uncertainty in a manner that is understandable by managers. This involves going beyond the parameter uncertainty narrowness to actual treatment of structural uncertainty, scenario uncertainty, and boundary uncertainty, which are very powerful in integrated water-carbon decisions.

6.5. MRV and Credibility Challenges for Carbon Outcomes in Water and Watershed Systems

Although MRV is a condition of carbon-neutrality

building, the plausible MRV is still unbalanced in water-related areas. Electricity and fuels may also be operationalized, and emissions can be easily monitored with sufficient metering and well-defined accounting regulations. Conversely, process emissions in wastewater systems are underestimated and often not measured at all when the generalized emission factors are used without local justification. Such measurement protocols improvement, site-specific emission factor methodologies, and process emissions estimation techniques as part of digital monitoring and control systems are therefore considered in the research agenda. In watersheds and nature-based interventions, due to spatial heterogeneity, ecological variability, reversal risk, and further complexity provided by methane emissions in saturated environments capable of neutralizing carbon storage increases, MRV is more uncertain^[72]. This is one major requirement, which is to separate accounting that is aimed at internal planning and accounting that is aimed at external claims or crediting, where the latter needs more intensive verification and treatment of uncertainty conservatively.

Also of importance is that there should be no duplication of counting and that there be uniformity in programs that overlap. The water quality trading, ecological compensation, and carbon market can be run within one basin, and hence complexity in governance. The accounting architectures required include research to be done on methods to monitor units of advantage across the programs, as well as to guarantee that a single ecological intervention is not or is not counted a number of times against various targets without any proper modifications. This issue is at the nexus of science, policy, and information systems, and it highlights the reason why integrated EMS design is a governance rather than a technical problem^[84].

6.6. Digital Enablement Research Priorities and Implementation Science

Digital tools are touted as a means to resolve the problem of integration, but literature reveals that technology does not provide an assurance of better decisions. One of the areas of priority is model and data governance: setting standards of data quality control, metadata, versioning, and auditability, and policies for managing model drift in non-stationary systems. Interoperability is another requirement, since integrated water carbon management needs

to integrate information between utilities, environmental agencies, land management departments, and occasionally even between private players, but this information may often be in incompatible formats with varying semantics. The studies of digital twins need to be focused, however, on not only the computational integration but also the validation strategies, operational deployment models, and human-system interaction, such as the impact of dashboards and decision-support outputs on actual decisions^[85].

Implementation science is also required to learn the ways in which integrated EMS structures can be incorporated into different institutional settings. Most basins have limitations in monitoring capacity, funding, and technical skills, and an agenda of SCI-standard should offer scalable paths like tiered implementation, in which essential metrics and rudimentary methods of diagnosis are implemented first, with upgrading as capacity expands. And lastly, equity and legitimacy should be considered as performance dimensions. Plans to achieve carbon-neutrality, which raise costs or limit access, may compromise the achievement of water security, and watershed interventions, which redistribute the burdens of land-use, can bring conflict in case benefits and costs are not evenly shared. Future studies ought to consequently incorporate indicators of social vulnerability and participatory governance systems into diagnostic and EMS systems, and ensure that the struggle to achieve carbon neutrality empowers, instead of undermining, the health and fairness of water systems^[5,86].

6.7.A Forward-Looking Roadmap for Research and Practice

Synthesizing between these gaps is an indicator of a progressive roadmap. To date, standardization of boundaries and core metrics, enhancements in transparency and uncertainty reporting, and the implementation of energy and emissions accounting in the normal water management process and in health diagnosis are most likely going to be the most effective developments in the near future. To make further strides, in the medium term, there will be a need to depend on hybrid diagnostic systems that will couple mechanistic understanding with forecasting based on data and will assist in robust portfolio optimization across multiple futures. Over the longer run, the field will be improved with validated basin-scale digital twins and whole

system, cross-sector, cross-jurisdiction governance architectures that can allow continuous learning and provable advancement towards not only healthy water systems but also carbon neutrality. This roadmap highlights the point that integration is not a final destination but an aspect of management that should be developed, sustained, and further enhanced as climatic, technological, and societal environments change ^[87].

7. Conclusion

This review has looked at the reorientation of water resources health diagnosis from being a more evaluative practice to being an operational base of environmental management systems geared towards carbon-neutrality construction. The synthesis demonstrates that the development of both healthy water systems and progress toward net-zero are more and more interdependent, but the current research and practice tend to address them as parallel lines. Water health evaluation continues to be principally by indicator aggregation and state ranking, with carbon-neutrality initiatives in the water sector often concentrating on energy consumption and facility-level inventories without considering the ecological limitations of basin-scale processes, emissions, and hydrological effects of land-based mitigation initiatives. The gap in question needs to be bridged not only with metrics and models, but also with the governance and verification routines that can be used to convert the diagnosis into sustained performance improvement.

In the literature, three requirements surface as critical in the construction of credible and scalable integrated systems. The former one is coherent at the boundaries. Integrated assessment can only be interpreted as the spatial, temporal, and accounting boundaries are clear and consistent, to understand what is included, what is excluded, and how the cross-scale effects are managed. The second is a disciplinary measure. A smaller set of core metrics—including hydrological regime integrity, priority pollutant pressures, ecological condition proxies, and resilience risk would have to be accompanied by carbon-relevant metrics, including energy intensity, operational emissions intensity, and in-ware material, process emissions of wastewater systems. Contributions related to the sink are to be handled distinctly between the uncertain and certain removals, and

the uncertainty, permanence, and non-CO₂ offset should be represented clearly. The third one is a closed-loop implementation. Environmental management systems offer an effective framework to correlate diagnosis with intervention portfolios and introduce measurement, reporting, and verification to ensure that the improvement is manifestable, auditable, and can be changed over time.

In terms of the methodology, the review emphasizes that a single approach to the diagnosis is not adequate in all situations. Composite indices and MCDA are useful in communication and prioritization, but must be supported by guardrails, sensitivity analysis, and transparent preference modeling to prevent the compensability pitfalls. Predictive and early warning models should be data-driven and controlled to manage non-stationarity, transferability, and interpretability in case they should guide interventions. Simulation models Process-based and integrated simulation models are still necessary in the context of scenario analysis and causal reasoning, but without calibration, validation, and propagation of uncertainty, in particular, when combining hydrology, water quality, ecology, and carbon accounting. The strongest course of action is thus in the hybrid: correlating method families with the purpose of decision and integrating them into cyclic EMS processes, in which endlessly refining diagnosis is done by monitoring.

Another aspect of the review relates to how digital enablement is only an enabler and not a replacement for sound design. Remote sensing, in-situ sensing, analytics, and digital twins can enhance the integration by enhancing the observability, speeding up updates, and assisting in planning and optimizing scenarios. Nevertheless, such technologies can only create value with robust data governance, interoperability standards, transparent model management, and institutional routines that transform insights into decisions. In the same spirit, the achievement of implementation requires harmonization of the incentives and duties of utilities, basin managers, land agencies, and climate governance institutions, as well as ensuring that equity and ecological thresholds are considered as limits and not optional factors.

On the whole, carbon neutrality construction and water resources health protection should be investigated as a non-stationary coupled management issue with cross-scale feedbacks and inevitable adjustments. To implement

the most viable research and practice direction, the most effective action is the development of integrated EMS structures that start with clear boundary delineation, standardized core measures with explicit uncertainty reporting, the use of hybrid diagnostic approaches to the context and purpose, and the realization of the intervention portfolio through MRV-based adaptive management. This ability will boost the plausibility of carbon-neutral statements in water and watershed initiatives, as well as the resiliency and wholesomeness of water facilities in the face of swifter climatic and socio-economic transformation.

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Conflicts of Interest

The authors declare no conflict of interest.

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