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REVIEW

Bridging the Gap: How Water Conservancy Projects Shape a Greener Future

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ABSTRACT

Projects on water conservation are gaining prominence as the primary intervention of climate adaptation, low-carbon development, and ecosystem restoration. However, their sustainability performance is exceptionally situational, guided by the basin hydrology, sediment interactions, operating regulations, and governmental capacity. This review summarizes the interdisciplinary evidence of how water conservation projects can be used to achieve a cleaner future by reducing the negative externalities, such as dams and reservoirs, irrigation and conveyance systems, flood control structures, managed aquifer recharge, and hybrid gray-green strategies. We establish an integrative model between drivers, interventions, system reactions, and results along four dimensions: environmental integrity, social equity, economic performance, and resilience to climate non-stationarity. Synthesis reveals that, co-benefits of scoring well, a fully functioning project operates in an adaptable way, evaluated on a basin level, and in conjunction with demand management and land-use planning. In contrast, net harms are mainly probable in the context of the flow regulation, where biodiversity is eroded due to flow fragmentation, downstream exposure to sediment trapping, water quality reduction due to residence-time effects, and salinization induced by irrigation, and the unequal distribution of benefits because of weak procedural protection. To address these gaps, the priority should be placed on retrofit and re-operation of the old assets, environmental flows, and sediment-conscious operation, scaling nature-based and hybrid solutions, and using digital monitoring and forecast-informed operations with transparent and responsible rules of decision-making. Lastly, the review identifies gaps in research, including standardized

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indicators, long-term monitoring, and causal assessment, and governance changes, and financing tools that incentivize proven sustainability performance as opposed to capacity building.

Keywords: Water Conservancy; Sustainability Transitions; Gray-Green Infrastructure; Climate Resilience; Environmental Justice

1. Introduction

Water has never been an overt agent of human progress, yet in the twenty-first century, it has turned out to be an open-ended condition of being able to decarbonize, adapt, and flourish. In all parts of the world, climate change, land-use change, and cities, industry, and agriculture are redefining the hydrological cycle [1]. Extreme rainfalls and compound floods are becoming more common, and longer and more severe droughts are occurring in most basins. Simultaneously, ecological degradation discontinuities, draining aquifers, contaminated waterways and disappearing wetlands have diminished the buffering capabilities of topography, which had traditionally smoothed the extremes of water. The combination of these overlapping pressures is making water management no longer a matter of sector, but a matter of central systems: water security has come to define the extent of food production, energy security, population health, biodiversity conservation, and economic sustainability. In this regard, water conservation initiatives, which in a broader sense learn to capture, transfer, control, and replenish water, are re-emerging as critical tools in determining a more environmentally-friendly future [2,3].

When one thinks of water conservation projects, the image that comes to mind is highly dams and reservoirs; however, the portfolio is far broader and more hybrid. It encompasses flood control and drainage systems, irrigation and conveyance systems, inter-basin transfers, river management works, controlled recharge of aquifers, developing investments in wetlands restoration, floodplain reconnection, and sponge-city measures that integrate engineered systems with natural processes. In the past, these projects were created with a one-dimensional purpose, such as increasing the amount of water available, increasing the irrigable acreage, or safeguarding assets behind the levees. Modern times require a more holistic approach to the conception of performance. Measuring the future green can be done through delivered cubic meters or preserved hectares, but it can also be by the outcomes of life-cycle greenhouse-gas emissions, the integrity and sediment continuity of an ecosystem, the results of water quality, the allocation of benefits and burdens to communities, and the resiliency of linked human-water systems in the face of fundamental climatic uncertainty. At this intersection stand water conservancy projects. They can facilitate low-carbon transitions, facilitate renewable energy systems, and manage energy-intensive water losses, and at the same time are key adaptation assets. However, they may also cause environmental damage and social injustice when they are not thought through with basin-scale restrictions and precautions. The practical and scientific necessity, thus, is to know how, when, and why these projects provide net-green outcomes [4,5].

The sustainability contribution of water conservation projects may be significant indeed, considering it from the perspective of system services as opposed to individual structures [6]. Storage - be it in surface reservoirs or aquifers - can mitigate the risk of droughts and stabilize municipal and agricultural supply to reduce the economic and social costs of water shortage. The purpose of flood attenuation and drainage infrastructures is to mitigate the occurrence of disasters, yet their functionality goes beyond disaster mitigation, as when combined with spatial planning and nature-based retention, they can also form multifunctional landscapes that could store water, recharge aquifers, cool cities, and support biodiversity. Non-revenue water and seepage can be decreased through conveyance and irrigation upgrades to enhance the efficiency and reliability of supply. Hydropower reservoirs in energy systems can supply dispatchable generation and flexibility services, which complement variable renewables, and pumped storage and coordinated operation can assist in managing peak demand. These direct benefits are further intensified by the digitalization: the real-time monitoring, remote sensing, and forecast-informed operations enable the operators to adjust releases and diversions on the fly, which would enhance performance at its very extremes and minimize unnecessary losses. Combined, these channels put water conservation as a facilitating platform to green development, which can equally serve both adaptation, mitigation, and resilience objectives [7].

Meanwhile, the historical account and the accumulating literature indicate that the water conservation initiatives have the capacity to produce poignant trade-offs. Habitat fragmentation, fish migration, changes in thermal regimes, and the inhibition of natural variability of flows that many species rely upon are possible due to river regulation and dams. Reservoirs cause the downstream reaches and deltas to starve as sediment trapped behind the reservoirs incises the channels, erodes the coasts, and exposes the region to rising sea levels. The quality of water can also decline: high nutrient loads can result in stratification and eutrophication in the reservoirs, agricultural runoff and salinization can occur with the development of irrigation and inadequate drainage. The net greenhouse-gas implications can be complicated, as far as climate is concerned. Although in certain settings hydropower can replace fossil generation, inundated biomass and watershed characteristics and operation regimes can result in methane and carbon dioxide emissions by reservoirs. Social consequences can have the same effects. Large projects have occasionally forced people to relocate, affected livelihoods, and aggravated inequities by having people benefit people far away, even as they suffer the cost. Projects that are protection-purposed may pose residual risk and maladaptive incentives; even levees and floodwalls may result in development in flood-prone areas, which cause people to suffer more after extreme events surpass the design limits. These facts help to realize that green is not a default feature of water conservancy. It is a product created- or sabotaged-by design decisions, operational decisions, governance decisions, and allocation of rights and duties [8–10].

Such tension of promise and danger is at the core of the gap to be bridged by water conservancy. The technological gap is not only technological, but technology is also important. It is also conceptual and institutional: between the infrastructure that is assessed in terms of narrowness and a water system that is seen as a coupled socio-ecological network; between short performance targets on a project level and long sustainability thresholds on a basin scale; between aggregate performance outcomes and fair outcomes; between a narrow understanding of the infrastructure and fair allocation of outcomes. The scientific literature on such areas has grown fast; however, it is still dispersed across the disciplines and types of projects. Reliability, storage dynamics, and flood attenuation are measured by hydrologists and engineers, habitat impacts, environmental flows, and connectivity by ecologists, costs, productivity gains, and avoided damages by economists, and lastly, governance, justice, and participation by social scientists. All the lenses are required, but judgments are not usually reached by combining them into logical, equivalent evidence. Because of this, discussions on water conservancy are making or may make extremes; some are making adaptations and developing to depend more on water, and others are highlighting irreversible ecological and social damages. We have to go beyond this polarization and seek ways toward a synthesis that elucidates mechanisms, metrics, and context dependence to establish ways of providing net-green outcomes [11].

Another problem is one of scale and causality. In Water conservation projects, the feedback and the rebound effects are experienced within basins. Irrigation or conveyance efficiency gains may have a paradoxical effect of causing total water use to rise in cases where they allow expansion or crop rotation, as has long been known in resource economics, and is becoming more noticeable in water management. Likewise, the flood defenses can decrease the occurrence of frequent losses and heighten exposure to rare extremes through changing land-use choices and perception of risk. These forces imply that assessing sustainability cannot only be done before and after comparisons in a project site as it can only be done by basin-level accounting and counterfactual thinking, taking into account how societies and ecosystems react over time. This is made more difficult by climate change, which undermines the idea that past hydrology can be a sufficient reference point to guide design and operation. Non-stationarity poses the questions of how to place value on flexibility, how to operate infrastructure at sequences of extremes, not single events, in designing infrastructure, and how to prevent maladaptation that will transfer risks to downstream communities or future generations. Greenness of water conservancy is therefore not just the physical object, but the governance at the same time: the clarity of decision-making, the adaptive operating rules, the involvement of all people, the maintenance funding on a long-term basis, and the protection offered to people and endangered ecosystems [12,13].

It is in this context that this review analyses how water conservancy projects create a greener future by integrating evidence on an environmental, social, and economic basis, as well as structuring results around mechanisms that relate interventions to outcomes. The review does not see dams, irrigation schemes, and nature-based measures as independent spheres, but it takes an integrated viewpoint, which captures modern trends in practice: the emergence of hybrid gray-green infrastructure, the growing role of digital water management, and the move towards multi-objective planning in the water-energy-food-ecosystem nexus. The point is not to either support or oppose specific types of projects using a blanket, but to determine the circumstances in which they provide net benefits and the design and governance tools that minimize trade-offs. This involves consideration of the effects of the life-cycle, operation-based emission, where evidence allows, ecological integrity of flow and sediment regimes, and social equity of benefits sharing, resettlement results, and procedural justice. The purpose of organizing the discussion in such a manner is to enable the researchers to harmonize methods and metrics and practitioners to make decisions that are strong, transparent, and sustainable development objectives. **Figure 1** provides a conceptual map of the causal pathway emphasized in this review, linking key drivers to conservancy interventions, system responses, and sustainability outcomes[6].

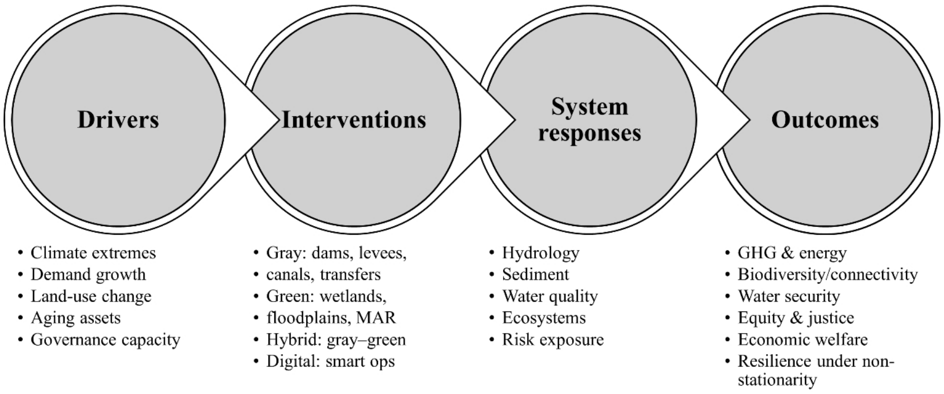

Figure 1. Conceptual map linking drivers, water conservancy interventions, system responses, and sustainability outcomes.

An effective framing is created through this perspective, which is that the future of water conservation is not an issue of either engineered or nature-based solutions but a matter of an intelligent synthesis of the two at the level of the basin[14,15]. Some areas of the greatest sustainability payback are retrofits and operational modernization of existing resources, such as improving environmental flow, facilitating fish passage, restoring sediment continuity wherever possible, reducing leakage and energy consumption, and selective green infrastructure that reinstates natural storage and filtration services. New construction can still be required in certain areas, especially where the stress of climate growth and demand increase exceeds available capacity; nevertheless, the justification of new construction must be determined by different measurements than previously, such as the accumulating effects, long-term dynamics of sediment transport, and distributional effects. Noteworthy, bridging the gap requires harmonization of incentives and institutions in the form of financing that incentivizes results and not capacity; regulation that takes into account cumulative and downstream impacts; and participatory procedures that lend legitimacy and conflict reduction. Lack of such alignment can result in underperformance of even technically advanced projects or net harm.

This review paves the way to water conservancy not as a classification of infrastructure, but as an active profession of system design with sustainability. The key idea is that water conservation initiatives can help to create a better green world by being constructed as multi-purpose interventions in coupled socio-ecological basins, which should be designed and operated with climate-wise flexibility, and controlled to safeguard the ecosystem to allocate gains equitably. The following pages summarize what has been learned regarding the way these results are attained, where evidence is inconclusive, and what the design of a future research and practice agenda should focus on. **Table 1** presents the categories of projects that have been included in this review and a summary of their common goals, co-benefit pathways, and common sustainability risks[16].

Table 1. Typology of water conservancy projects, dominant functions, and sustainability-relevant implications.

Category	Typical Project Types	Dominant Service Objectives	Main Sustainability Co-Benefit Pathways	Common Sustainability Risks/Trade-Offs
Gray infrastructure	Dams/reservoirs, levees/floodwalls, canals, inter-basin transfers, drainage networks	Storage, diversion, flood protection, hydropower generation	Drought buffering; flood peak reduction; hydropower flexibility; improved delivery reliability	Flow regime alteration; fragmentation; sediment trapping; water quality stratification; displacement; residual flood risk and induced exposure
Green infrastructure	Wetlands, floodplain reconnection, riparian buffers, watershed restoration	Retention, filtration, habitat support	Peak-flow attenuation; water purification; habitat connectivity; microclimate cooling; carbon storage (site-dependent)	Land competition; performance variability; maintenance and governance dependence; benefits may accrue slowly
Hybrid gray–green	Setback levees + floodplains, reservoirs + environmental flow programs, urban sponge systems + drainage	Multi-objective risk reduction and service provision	Multi-functionality; reduced residual risk; improved water quality; enhanced ecological outcomes for similar service levels	Higher coordination needs; monitoring and adaptive management requirements; complex benefit attribution
Operational/digital upgrades	Forecast-informed reservoir operation, telemetry/IoT, leak detection, optimization/AI decision support	Improve performance of existing assets	Increased effective yield; reduced losses and energy use; improved drought/flood response	Data gaps; cybersecurity; algorithmic opacity; inequitable rule setting if governance weak

2. Theoretical Framework and Review Methodology

2.1. Conceptual Foundations for Linking Water Conservancy to Sustainability Outcomes

This review is based on the assumption that water conservation projects are not engineering artifacts, but elements of coupled human-water-ecosystem systems. They affect them in biophysical processes, institutional setups, and behavioral reactions that have spatial and temporal dimensions. The review utilizes four mutually supportive theoretical lenses in order to arrive at an analytically rigorous yet decision-relevant interpretation of this complexity. To start with, the theory of sustainability transitions is applied to see water conservancy as a part of long-lived infrastructure regimes that may speed up the processes of decarbonization and resilience or lead to path dependence and lock-in. Since dams, levees, and conveyance networks regulate the developmental paths over decades, their sustainability performance cannot be estimated at commissioning only, but it should be evaluated as a dynamic path formation performed by the operational regulations, maintenance capacity, and changing climatic baselines[17].

Second, the perspectives of socio-hydrology and coupled human-natural systems inform the manner in which feedbacks develop between the infrastructure and the hydrological variability and how societies accommodate them. Such views are critical in explaining such phenomena like growth in demand as a result of perceived supply reliability, a change in risk perception that underlies flood defenses, and the shift of vulnerability along upstream-downstream and rural-urban gradients[18].

Third, the water-energy-food ecosystem nexus is embraced as an integrative prism to encompass cross-sector interactions and trade-offs. Conservation projects involving water have the potential to provide a wide range of services at the same time, e.g., irrigation water, flood reduction, hydropower flexibility, and ecological flows; however, maximizing one service may decrease another. Nexus thinking is the way of interpreting these interactions as system-level co-benefits or externalities, instead of being sectoral outcomes that are unrelated to each other[19].

Fourth, distributional, procedural, and recognitional aspects of sustainability are anticipated by using the environmental justice theory. Numerous controversial results are related to water conservancy more than the ecological disruption or the ineffectiveness of decisions, but the distribution in terms of power of decision-making, the validation of knowledge, and the allocation of advantage and disadvantage among communities, generations, and jurisdictions. By incorporating the aspects of justice in the review, it is possible to have a more comprehensive evaluation of how green the field[20].

2.2. Integrative Analytical Framework Adopted in This Review

In the continuation of these theoretical lenses, the review uses an integrative structure where evidence is organized based on causal mechanisms between drivers and interventions, system responses, and sustainability outcomes. The framework commences with exogenous and endogenous drivers like climate variability and change, demographic and economic development, land-use change, regulatory restrictions, and institutional capacity. It is these drivers that influence the choice of interventions, these being area coverage in gray infrastructure (e.g., dams, dikes, canals), green infrastructure (e.g., wetlands, floodplain restoration, managed recharge landscapes), hybrid gray/green design, and operational or digital upgrades changing the operation of existing assets[21]. Based on the sustainability transitions, socio-hydrology, nexus thinking, and environmental justice, **Figure 2** offers the integrative analytical framework applied to organize evidence and interpret context dependence.

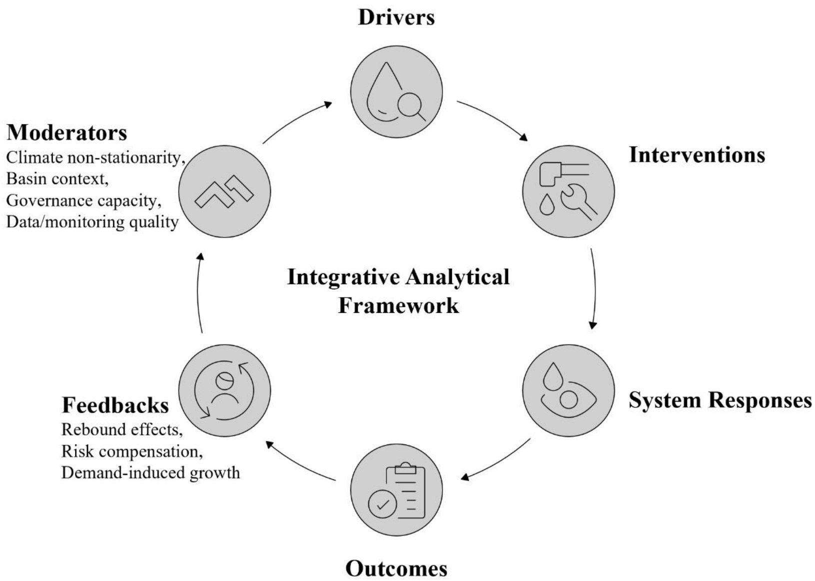

Figure 2. Integrative analytical framework for evidence synthesis (Drivers, Interventions, Responses, Outcomes) with feedback and moderators.

Interventions have system reactions in various ways. The changes brought by them, hydrologically, are in terms of storage, timing, magnitude, and variability of streams; they can alter interactions between groundwater and surface water, as well as reduce the flooding wave and flood buffering potential. They impact the temperature regimes, nutrient cycling, dissolved oxygen, and pollutant transport biogeochemically[22]. They alter the sediment continuity and channel-floodplain connectivity, geomorphologically. On the ecological level, they transform habitats, levels of connection, and disturbances that support the biodiversity and ecological services. They modify social and economic risks, water supply dependability, agricultural and industrial output, and water demand and land development patterns, which are the motivators of water[23].

Results are then measured using four sustainability dimensions, which are repeated across disciplines: the environmental performance, which includes implications of greenhouse gases; the quality of water, biodiversity, and the dynamic of sediments; the social performance, which includes the outcomes of people living near the compound extremes and deep uncertainty; the resiliency performance, which refers to the capacity to maintain the intended services under compound extremes[24]. The unique aspect of the framework is that it pays particular attention to the feedback and rebound effects. The efficiency gains, such as could lead to a decrease in the conveyance losses but an increase in the consumptive use by growth or intensification, and flood defenses could lead to a decrease in the frequency of losses and an increase in the exposure to the extreme events by the development in the areas that are under protection. This feedback has been considered as part of the sustainability assessment as opposed to being considered as peripheral complications.

2.3. Review Design and Reporting Standards

This review is based on a systematic synthesis methodology with a systematic search that is consistent with the PRISMA 2020 protocol (Page et al. 2021). A review protocol was registered before the review was started. The synthesis is generally of a narrative and mechanism type, recognizing that there are various contexts, metrics, and types of projects that are heterogeneous. If studies have similar indicators for similar interventions, direction-of-effect synthesis with quantitative synthesis is reported as meta-summary, and baseline variation and system boundaries carefully considered [25].

2.4. Search Strategy, Information Sources, and Study Identification

The literature search will be focused on peer-reviewed journal articles and review papers, which will be supplemented by high-quality institutional reports where necessary, due to the technical detail that is not always available in journals [26]. Core bibliographic databases usually encompass Web of Science and Scopus, and are often extended to include engineering village or discipline-specific repositories to include any hydraulics, hydropower, and water resources engineering research that might be underrepresented elsewhere [27]. The search window has been chosen to a timeframe where sustainability assessment methods, nature-based solutions, and climate-informed operations started to be prominent in the literature, even though the foundational work on environmental flows, large dam impacts and irrigation modernization has been included [28].

The search strings are built by using the terms that capture the categories of interventions and the terms that capture the outcomes and evaluation methods. Some of the intervention terms include dams and reservoirs, hydropower, flood control and levees, drainage networks, irrigation and conveyance modernization, inter-basin transfers, managed aquifer recharge, wetlands restoration, floodplain reconnection, and sponge-city/low-impact development strategies. The outcome terms that are put down include sustainability, resilience, adaptation to climate change, greenhouse emissions, life-cycle analysis, ecosystem service, transport of sediments, biodiversity, water quality, equity, as well as governance. Methodological words are added to define studies with the use of modeling, scenario analysis, multi-criteria decision analysis, hydro-economic optimization, and remote sensing [29]. Refining of the search is performed by trial and error to ensure that known sentinel papers are retrieved and also by refining terms to accommodate disciplinary variation in terminology [30,31].

2.5. Eligibility Criteria and Screening Procedure

Inclusion criteria: (1) Peer-reviewed journal article or good quality institutional report; (2) Empirical, modelling or systematic governance analysis assessment; (3) Assessment of ≥1 of the water conservancy intervention types listed in **Table 1**; (4) Report of ≥1 of the sustainability outcomes listed in **Table 1** (environmental, social, economic or resilience); (5) Adequate methodological detail to be quality appraised. Exclusion criteria: Opinion pieces/editorials/Conference abstracts with no data; Studies where water intervention is not the subject of the study (e.g., general hydrology, no connection to conservancy); Methodologically insufficient (No baseline/no counterfactual/insufficient description).

Titles/abstracts were screened independently by two reviewers (Zhang J., Zeng Q.H.) and $\kappa = 0.82$, and then screened full texts, $\kappa = 0.79$. No disagreements (n = 0) were resolved by a third reviewer (independent academic). Initial hits (n =3 ,847), after removing duplicates (n = 2,931), title/abstract screened (n = 2,931 → n = 412), full-text assessed (n = 412 → n = 267), final included (n = 267) are documented in PRISMA flow diagram. The latter rule—for overlapping publications from the same project - applied in the case of 31 publications, for which the most methodologically complete and recent was retained [32–34].

2.6. Quality Appraisal and Risk-of-Bias Assessment

Due to the combination of evidence using various methodologies in the review, quality appraisal is specific to the study type instead of using a general rubric. In the case of empirical studies, it gives importance to sampling, coverage through time, control of confounding, and the existence of credible baselines or counterfactuals in comparison. The fundamental criteria that need to be considered when studying modeling include transparency of assumptions, model selection as appropriate to the research question, calibration and validation process, uncertainty treatment, and sensitivity analysis. In the case of life-cycle assessments, appraisal objectives relate to defining a system boundary, quality of inventory, allocation techniques, the selection of functional units, and the availability of results along with uncertainty range and scenario testing. In cases of governance and social-impact research, this appraisal complexity puts the emphasis on the case selection clarity, data sources triangulation, qualitative analysis rigor, and the explicit positionality, presentation, and ethical issues treatment.

The risk of bias is addressed in the same way, i.e., publication bias favoring big/high profile projects, geographic bias in favor of regions with better monitoring and reporting, and outcome-reporting bias whereby positive performance metrics are more likely to be recorded compared with negative externalities. These risks are dealt with in the review by recording the regional and thematic coverage, reading the null results and negative findings as such, and making claims of success conditional on whether the reported outcomes are complete.

2.7. Data Extraction, Coding Scheme, and Evidence Synthesis

Data extraction is structured on a standardized coding schema that is in line with the integrative framework. Studies are coded in terms of type of project and intervention, geographic location, and context of the basin, climatic regime, major objectives of the intervention, and the type of evaluation used. The results are coded on environmental, social, economic, and resilience scales, where the definition and units of indicators are carefully noted to discourage the use of false comparability. The extraction also captures the time scale of analysis, the existence of downstream or cumulative effect assessment, the level of description of the governance arrangement, stakeholder engagement, and benefit-sharing mechanisms [35].

Production is built up. The initial layer is a descriptive mapping of the base of evidence that defines the types of interventions and outcomes researched the most and geographic gaps that still exist. The second layer makes comparisons across categories and contexts of interventions, finding similar patterns in the co-benefits and trade-offs and conditions that mediate performance, including sediment regime, land-use intensity, governance capacity, and climate stress. The third is mechanism-based, in which the cause-and-effect relationships of the effects of particular choices in design, rules governing operations, and governance structures are followed. When the studies have commensurable measurements, e.g., the attenuation of flood peaks, reliability indices, water quality indicators, or life-cycle greenhouse-gas estimates, the results are normalized where possible and viewed in the perspective of system limits and baselines. In cases of limited commensurability, the direction of convergence of evidence is stressed in the review, as well as explanatory coherence, but not numerical aggregation. **Table 2** summarizes some of the most popular environmental, social, economic, and resilience indicators and matches them with data sources and assessment techniques in order to enhance comparability between studies [36].

Table 2. Core indicator set for evaluating the net-green performance of water conservancy projects.

Sustainability Dimension	Indicator Family	Example Metrics (Typical Units)	Recommended Data Sources	Common Methods
Environmental	GHG & energy	Life-cycle GHG (kg CO_2e per m³ delivered/per kWh); operational energy (kWh per m³)	LCA inventories; utility energy logs; grid emission factors	LCA/LCIA; process-based accounting; scenario comparison
Environmental	Water quality	Nutrients (mg/L), turbidity (NTU), DO (mg/L), temperature (°C), salinity (EC)	Monitoring stations; remote sensing (where applicable)	Trend analysis; mass balance; coupled hydrodynamic–water quality models
Environmental	Ecosystems & connectivity	Environmental flow compliance (%); habitat/connectivity indices; fish passage effectiveness (%)	Eco-monitoring; river network data; tagging studies	Environmental flow assessment; BACI designs; ecological modeling
Environmental	Sediment & geomorphology	Sediment continuity metrics; reservoir sedimentation rate; downstream channel change	Bathymetry; sediment gauging; geomorphic surveys	Sediment budgeting; morphodynamic modeling; long-term monitoring
Social	Equity & justice	Distribution of benefits/costs; resettlement livelihood outcomes; participation quality	Household surveys; project documents; interviews	Mixed-method evaluation; distributional analysis; governance analysis
Economic	Cost & value	NPV including avoided damages; O&M adequacy ratio; productivity change	Project finance reports; agriculture/industry data	Cost–benefit + sensitivity; hydro-economic modeling
Resilience	Reliability under extremes	Reliability/resilience/vulnerability indices; stress-test performance	Hydro-climate records; downscaled scenarios	Robust decision-making; stress testing; scenario analysis

2.8. Methodological Limitations and Scope Conditions

The evidence base has several limitations, which are addressed expressly in this review. The former is heterogeneity in the choice of indicators and system demarcation, specifically in greenhouse-gas accounting, ecosystem service, and economic appraisal, which makes it difficult to directly compare across investigations [37]. The second is unequal monitoring capacity and data availability in the various regions, thus causing the geographic concentration of evidence and possible underrepresentation of impacts in data-deficient settings. The third is the difficulty in attributing the result to the interventions within basins that are dynamic, where there are numerous policies, land-use changes, and climatic changes that are interacting. The fourth is when there is an individual mismatch with time, as short evaluation windows do not capture the long-term sediment processes, shifts in ecological regime, or reduction in performance due to maintenance.

Such constraints guide the manner in which conclusions are formulated. The presentation of findings is conditional based on context, design, operation, and governance, and claims are weighted based on the quality of evidence and methodology transparency. The explicit definition of these scope conditions intends to present a plausible basis for interpreting how water conservancy projects can bring the future closer to being greener, and to determine where more powerful approaches and data are required to underpin the process of making sound decisions.

3. Sustainability Pathways and Co-Benefits

3.1. Framing Co-Benefits through Service Pathways

Water conservancy policies affect sustainability in the sense that the reliability, timing, and quality of water-related services relied on by societies and ecosystems are altered [38]. These services will also involve water delivery to domestic, industrial, and agricultural demands; flood control; conservation of ecological functions like seasonal flooding, transport of sediments, and availability of habitats. The co-benefits that have been discussed in this section are thus not considered as the isolated benefits of a particular structure, but as the consequences arising from the channels that exist in connecting interventions to system responses and, thereafter, environmental, social, and economic performance. This framing of pathways is critical as the same intervention may have significantly varied sustainability results based on basin characteristics, operational guidelines, capacity to govern, and past stressors in the background, like land-use intensity and climate variability. It also underscores the fact that a great number of co-benefits are conditional; they tend to be more likely to be realized when projects are specified and managed as multi-purpose systems than when they are specified and managed as single-purpose assets.

3.2. Water Security Enhancement and Drought Resilience

Enhanced water security conditions in inferring hydroclimatic conditions characterized by growing instability is one of the most often mentioned sustainability contributions made by water conservancy [39]. Storage infrastructures such as surface storage and managed aquifer recharge systems have the capacity to smooth seasonal and interannual changes by redistributing water over time. This buffer effect lessens the likelihood and intensity of supply shortages of cities and industries and has the capability of stabilizing farm output in areas where rainfall variability is a constraint. Sustainability is also relevant to this pathway, not only due to the higher volumes of supply but also due to the lower vulnerability. In cases where the effects of drought are eliminated, there is less need for emergency actions, including unplanned groundwater pumping, costly water trucking, or hasty growth of energy-intensive supply alternatives. In that regard, the environmental pressures, which tend to accompany the responses to the crisis, may be mitigated in an indirect manner by well-managed storage.

The fruit of drought resilience is more and more directly associated with operational sophistication as opposed to storage capacity itself. Operating in accordance with a forecast, enhanced hydrological surveillance, and dynamical allotment principles can enhance the efficient productivity of current systems by allowing action to be taken in response to arising drought conditions sooner and proportionately. Where the available co-benefits of storage are constrained by inflexibility in basins where over-allocation or an institutional fragmented system of governance restricts flexibility; and where a consistent rationing and coordinated operation by surface and groundwater over a whole basin is feasible by creating a system of governance that provides transparency, the identical physical resources can achieve a higher level of reliability and reduced level of ecological disturbance. Managed aquifer recharge is a rather significant route in water-stressed areas as it can increase storage without most of the evaporation losses and surface-area footprint that reservoirs have. Recharge combined with protection of source water and water quality can produce both quantity and quality co-benefits, such as stabilizing groundwater quality and reducing salinity intrusion in coastal aquifers, as well as control of intrusion by other pollutants [40].

3.3. Flood Risk Reduction and Climate Adaptation Services

One of the fundamental purposes of most water conservancy projects is flood control, and the contribution of sustainability is best seen in the prevention of loss of lives, damages to property, and growth of economic activity. Floodwalls, retention basins, reservoir flood pools, and levees are some structural measures that can reduce the frequency of destructive inundation to the set standards of protection. Nonetheless, it is not only the protection of pre-existing development where the relevance of flood risk reduction in the green future can be found. Combining flood management with basin planning will provide a transition between reactive disaster management and proactive climate management, which will offer a chance to balance risk reduction with ecological recovery and urban life quality [41,42].

The co-benefit pathway whereby gray flood defenses are coupled with green retention and reconnection measures is an important one. Recovered floodplains and wetlands can dilute peak flows and infiltration and diminish downstream flood peaks, coupled with habitat and water purification, and recreation. In cities, sponge-city and low-impact urban development strategies, including permeable surfaces, green rooftops, and detention landscapes, can reduce the amount of runoff and maximum discharge and enhance the microclimates and air quality. Such measures usually enhance readiness against brief intervals of heavy rain that surpass normal drainage pipes. The sustainability rationale is that distributed retention and infiltration minimize the effects of flood risk and water quality impacts of combined sewer overflows and stormwater pulses of pollutants. Integrated flood management can hence provide a portfolio of co-benefits in terms of safety, ecology, and well-being to the people were designed in an integrated manner [42].

3.4. Energy and Decarbonization Linkages within Water Conservancy

The water conservancy projects also overlap with decarbonization in several ways, such as electricity production, flexibility of the grid, and energy intensity of water supply [43]. The most direct connection is hydropower, which in most cases provides low-emission-of-operation electricity and, most importantly, dispatchable electricity, which can supplement variable renewables. Balancing services, frequency regulation, and peak capacity in high wind and solar systems can be provided by the use of reservoirs and pumped storage, lessening the need to use fossil-based peaking generation. Such flexibilities can be overvalued in climate terms of the approach of energy only accounting, since this impacts the extent to which renewable capacity can be integrated reliably.

In addition to hydropower, there are co-benefits associated with energy, whereby the modernization of water conveyance and distribution minimizes the loss and pumping requirements [44]. Electricity to pump a unit of delivered water can be minimized through leakage control, pressure management, and optimization of the canals, particularly those with long conveyance distances or great elevation differences. Equally, computerized control systems are able to set the timing of the pumping to use electricity when it is cheap or to evade peak loads. In irrigated agriculture, the better delivery reliability will lower farmers' reliance on groundwater pumping, which, in most cases, is energy-intensive and with high indirect emissions. These channels reveal that water conservation can not only be used to decarbonize through the generation of electricity, but also via the decrease of the energy footprint of water services. The size of these benefits, though, varies depending on the conditions of the base and the amount of carbon contained in the source of energy, which is why claims of this kind must not be made generically but in a context-specific manner.

3.5. Ecosystem Services, Co-Benefits, and Ecological Rehabilitation Potential

Even though water conservation has typically been linked to ecological disturbance, another significant sustainability trajectory is the ability of projects, specifically those that are planned as hybrid or restorative interventions, to promote or improve ecosystem services [45]. Natural and combined interventions can re-establish hydrological processes that maintain biodiversity and ecosystem output, such as groundwater recharge, seasonal flooding, and the connection between rivers and riparian areas. Wetlands restoration and floodplain reconnection may enhance the nutrient retention and carbon sequestration of soils, as well as enhance the habitat heterogeneity. In others, seasonal flow patterns, including fish spawning, riparian vegetation recruitment, and channel feature maintenance, can be partially restored by re-operating the reservoirs to supply environmental flows.

The benefits of improving water quality via ecosystem co-benefits also occur when any of the conservational measures decrease the load of pollutants or extend the range of variability in temperature and turbidity [46]. Nutrients and sediments can be eliminated through constructed wetlands and retention ponds, which enhance the quality of water downstream and lower the costs of treatment. The riparian buffers and watershed reforestation can mitigate erosion and stabilize the banks, which can improve sediment management and diminish the effects of turbidity. The co-benefits may be synergistic where such measures are part of larger basin plans: better water quality facilitates aquatic ecosystems and lowers the energy and chemical requirements of water treatment, and not only does the ecology and climate outcome have a relationship.

3.6. Agricultural Productivity, Food Security, and Rural Livelihood Pathways

The irrigation and water delivery systems are still a core aspect of water conservation in most areas, and their sustainability impacts have always been explained in the context of crop yield stability and food security [47]. Consistent irrigation has the potential to lessen the risk of fluctuating rainfall and allow better-value production systems to be used, which increase rural incomes and promote economic growth in the region. The co-benefit route is especially relevant in the context of climate change, where the production risk rises due to the emergence of heat stress and changes in precipitation. Assuming that the reliability of delivery and precision of schedule can be enhanced, the loss of crops during periods of drought can be minimized with these types of investments, and the productivity of water can be improved.

But co-benefits that are relevant to sustainability are beyond yield measures. Equity in the distribution of water as a modernization in the irrigation districts can minimize the conflict and enhance social welfare, especially when tail-end users are disadvantaged [48]. With proper drainage and salinity control, conveyance upgrades can mitigate waterlogging and soil degradation and therefore safeguard the agricultural landscape's productive base in the long term. Moreover, better irrigation stability will decrease the necessity of emergency pumping of groundwater, further decelerating the rate of aquifer depletion and decreasing the consumption of energy. These interlacing tracks demonstrate that the agricultural co-benefits are conditional upon the joint performance of infrastructure, institutions, and agronomic practices, and are motivated by the need to prevent overstating of benefits, which could be counterbalanced by higher total consumption or downstream effects.

3.7. Urban Water Reliability, Public Health, and Economic Continuity

Water conservation projects in the fast-urbanizing areas are therefore more justified based on the need to maintain a stable supply of water around the municipal and industrial sectors [49]. The advantages of reliability help in the protection of the health of the population since the chances of service interruption that can affect the sanitation and the risk of infection are reduced. They also aid economic continuity by cushioning the economic sector that is reliant on water and lowering the expenses involved in rationing and emergency purchasing. These advantages are especially useful in cities that either depend on single-source supplies or are susceptible to the conveyance routes.

Urban sustainability cascades are increased as the conservancy strategies combine supply security and demand management, and distributed green infrastructure. The ecological footprint of urban water can be reduced through investments in leakage reduction and pressure management, which can provide significant returns to the effective supply without increasing the ecological footprint of urban water through new withdrawals. Local recharge and stormwater capture can be used to add to supplies as well as minimize flood risk and enhance urban microclimates. The multi-functionality of the co-benefit pathway in this case is as follows: interventions that are presented as water management can provide parallel benefits in terms of disaster reduction, heat reduction, and neighborhood amenity [50]. Like any other pathway, these benefits vary in the institutional capacity and sustainability, as operations that are not funded well may destroy performance despite well-designed initial designs.

Through the above pathways, there has been an overall trend; co-benefits are strongest when water conservancy projects are designed as part of integrated basin plans and run flexibly in response to climate uncertainty [51]. Even the projects that are created with a one goal in mind can have co-benefits that occur by chance, yet such projects are not as predictable and are more vulnerable to the occurrence of externalities that remain unaddressed. Multi-objective design and operation, aided by monitoring, clear allocation policies, and systems to support stakeholder engagement, in contrast, can change trade-offs into manageable tensions and improve the likelihood of alignment between environmental, social, and economic outcomes.

Another important point in this synthesis is that co-benefits are usually attained in combinations of interventions and not in single structures. These include demand management, coordinated groundwater management, flood risk management, land-use planning, distributed retention, decarbonization, operational optimization, and low-carbon electricity integration, management of ecosystem services, environmental flows, connection, and watershed rehabilitation. By identifying these combinations, the analytical interest of the project performance is redirected toward system performance, which offers a more realistic ground on which water conservancy could be used to bring about a greener future and preconditions the following part, which discusses the trade-offs and risk hotspots that may subvert such benefits [52,53].

4. Trade-Offs, Externalities, and Risk Hotspots

4.1. Why Trade-Offs Are Central to "Green" Evaluation

The unintended impacts of a water conservancy project just as much determine its sustainability performance compared to the intended services [53]. The fact that interventions involving the stabilization or redirection of water change the physical template upon which ecosystems and societies have evolved and space, and that the benefits and costs of these interventions are not equally distributed over space, time, and social groups, creates trade-offs. These processes are aggravated by the time permanence of the water infrastructure, and by the non-stationarity of weather and land use. Consequently, what seems to be a valuable intervention under the scrutiny of a short-term goal, whether it is the reliability of supplies or the prevention of floods, can have net negative outcomes when the larger environmental, social, and intergenerational consequences are taken into consideration. The trade-offs in this section are grouped on the key risk hotspots that are used across project types and focus on the mechanisms of impact and the circumstances to exacerbate or mitigate them. **Table 3** provides a summary of key externality pathways, determines practices that can benefit by creating warning signals that can be applied at an early stage, and connects hotspots to mitigation or management responses that are usually implemented.

Table 3. Trade-off hotspots: Mechanisms, signals, and mitigation/management levers.

Hotspot	Primary Mechanism	Who/What Is Affected	Early Warning Signals (Examples)	Mitigation/Management Levers
Loss of flow variability	Regulated releases dampen peaks/seasonality	Aquatic biota, riparian recruitment, fisheries	Reduced floodplain inundation frequency; altered temperature regime	Dynamic environmental flows; adaptive operating rules; floodplain reconnection
Fragmentation/connectivity loss	Barriers impede migration and gene flow	Migratory fish, riverine biodiversity	Declining migratory species; reduced spawning success	Fish passage/bypasses; fish-friendly turbines; barrier prioritization at basin scale
Sediment discontinuity	Reservoir trapping starves downstream	Channels, deltas, coasts; downstream livelihoods	Increasing reservoir sedimentation; delta retreat/erosion	Sediment bypass/flushing; dredging with beneficial reuse; coordinated reservoir operations

Table 3. *Cont.*

Hotspot	Primary Mechanism	Who/What Is Affected	Early Warning Signals (Examples)	Mitigation/Management Levers
Water quality degradation	Stratification/eutrophication; irrigation salinity	Drinking water, ecosystems, soils	Algal blooms; low DO; rising EC/salinity	Selective withdrawal/aeration; nutrient load controls; drainage/salinity management
Climate trade-offs (GHG)	Construction emissions; reservoir methane	Climate goals, project credibility	High embodied carbon; methane hotspots	Low-carbon materials; improved reservoir management; life-cycle accounting and monitoring
Social inequity/displacement	Unequal burden sharing and weak safeguards	Local/indigenous communities; vulnerable users	Conflict; livelihood decline; procedural exclusion	Benefit-sharing; robust resettlement/livelihood restoration; participatory governance

4.2. Ecological Disruption from Flow Regulation and Habitat Fragmentation

One of the standard externalities of the gray water conservancy infrastructure is the disruption of flow regimes [54]. Controlled diversions and dams tend to diminish the size and occurrence of high flows, change the seasonality, and tone down variability. The changes are able to simplify the habitats, disrupt the life-cycle cues of aquatic organisms, and change the disturbance pattern that sustains the floodplain and riparian ecosystems. The loss of natural variability may lower ecological integrity even with minimum flows of water due to the dependence of seasonal pulses in ecological functions by many species, such as spawning, migration, nutrient exchange, and habitat renewal. Temperature regimes may also change due to flow regulation, especially when releases are made out of cold hypolimnetic layers, or when dams enhance solar heating; these thermal changes may be used ecologically when temperature limits determine species patterns in rivers.

These are hydrological effects that are further complicated by fragmentation. Longitudinal connectivity obstructions interfere with the migration and gene flow of fish populations, and the absence of lateral connectivity separates rivers and wetlands [55]. The ecological cost is not restricted to charismatic migratory fish, but it is propagated to food web structure, riparian vegetation recruitment, and exchange of organic matter and nutrients that aid productivity. Cumulative fragmentation by a variety of structures in most basins has put in place network-wide limits to recovery, even in cases where single projects are alleviated. This is the reason why the project-by-project impact assessments can systematically underestimate ecological risk unless cumulative effects and the connecting context of any of the interventions are taken into consideration.

4.3. Sediment Trapping, Geomorphic Change, and Downstream Vulnerability

Sediment dynamics manifest as a salient trade-off that is usually underestimated during initial planning but becomes critical throughout the existence of a project. The downstream channels, floodplains, and deltas are deprived of sediments, which replenish rivers through reservoirs and river regulation works. Trap sediments may, over time, cause degradation of the designed performance as well as decrease the storage capacity of the reservoir and destabilize the banks, and deteriorate geomorphologically diverse-based habitation, as well as leading to channel incision downstream. In deltas and coastal areas, a slowing of sediment supply may cause land subsidence and shoreline withdrawal, increasing the vulnerability to sea-level rise and storm surge. The downstream vulnerabilities may be translated into other significant socioeconomic expenses, such as loss of agricultural land, destruction of infrastructure, and rising salinity intrusion [56].

The related trade-offs of sediment are particularly severe in the context of climate change since extreme events can mobilize high pulses of sediment, and the altered patterns of run-off may cause a shift in the regime of erosion. Systems that use reservoirs to provide flood protection can have decreased flood storage capacity due to increased sedimentation at the time when flood buffering is most required. Furthermore, geomorphic impacts of sediment starvation tend to occur over several decades, which triggers a non-congruence between brief appraisal horizons of short-term projects and long-term sustainability effects. This time, disconnection has the potential to create intergenerational injustices: modern users have the advantage of utilizing the services of regulation and future communities to pay the price of losing the delta, habitat failure, and storage depletion [57,58].

4.4. Water Quality Deterioration and Biogeochemical Side Effects

Water quality may be enhanced in some situations by water conservancy interventions, and these interventions may also be lost through processes that depend on residence time, stratification, and biogeochemical cycling changes. Impoundments have the effect of increasing the water residence time, which may favor algal blooms in the event of high nutrient loads. Stratification may contribute to the development of either hypoxic or anoxic waters in the bottom waters that influence aquatic organisms and cause changes in nutrient release of sediments. The outflow of such systems may carry low oxygen water, change in temperature regime or nutrient pulse affecting the health of the river. Besides this, controlled flows can decrease the ability of rivers to sweep away contaminants, which causes pollution to be concentrated during floods and puts downstream users in greater treatment costs [59].

Another group of water quality risk is brought by irrigation and drainage networks. The more aggressive irrigation will mobilize the salts and agrochemicals and cause salinization, contamination of nitrates and pesticide residues in surface and ground water [60]. In areas where drainage is poor, land can be waterlogged (leading to soil degradation and decreased long-term productivity) and salivated (turning short-term increases in yield to long-term increases in land degradation). The trade-offs of this nature that are made under quality considerations are particularly hard to undo since they are systemic to the workings of the landscape, and impacted by the policy incentives, land tenure, and agricultural practices that fall outside of the water industry.

4.5. Greenhouse-Gas Implications and Climate Trade-Offs

Water conservancy projects have complex climate implications that are context-specific. Building of massive gray infrastructure may be carbon-intensive because of building materials like cement and steel, earthworks, and transportation. The indirect emissions of operation may be because of the energy used in pumping and treatment, which depends on the carbon intensity of electricity. In the case of reservoirs, direct release of methane and carbon dioxide may take place through the breakdown of organic substances in an anoxic environment, where the scale of emission is extremely unevenly distributed across climate zones, biomass covered, nutrient conditions, and reservoir age. These emissions make simple stories where hydropower is regarded as the unproblematic, low-carbon, and emphasize why life-cycle assessment and site-specific measurement are essential in plausible climate accounting [61].

The trade-offs that can manifest in the climate due to new water availability could also be based on land-use change. Increases in irrigation and agricultural activity may raise fertilizer and land-use emissions, and decreases in river flows may decrease carbon sequestration in downstream wetlands and floodplains. Nature-based measures, on the other hand, can capture carbon, but they need an area that can be used for other activities. Such interactions demonstrate that the carbon balance of water conservation cannot be evaluated separately and, instead, that such processes need to be evaluated in the context of the larger socio-ecological system and through the supply chains and land-use pathways that the project facilitates [62].

4.6. Social Displacement, Livelihood Impacts, and Equity Concerns

The legitimacy and long-term viability of water conservancy projects are usually dictated by the social externalities of these projects. Huge reservoirs and conveyance channels have the potential to relocate communities, interfere with cultural heritage, and change the local ways of life that rely on riverine ecosystems, floodplain agriculture, or fisheries. Even with compensation, the results may not be equitable especially when resettlement programs fail to maintain access to land, employment, and social networks. These effects are not transitional only; they can be long-term, as they can be embodied in education, health, and economic opportunities [63].

Displacement is just one of the equity concerns. Urban centers, industrial users, or downstream irrigators often get the benefits of projects, and upstream communities incur the environmental burdens and opportunity costs. With a transboundary or inter-jurisdictional basin, allocation determination may enhance politicization and end up with losers and winners among regions. The procedural inequities may also occur due to a lack of voice of the affected communities in the planning process, where the environmental impact assessment is not conducted transparently, or when technical knowledge is applied as a mechanism to marginalize local knowledge. Recognitional justice is also applicable, especially at the level of indigenous groups that do not have economic relations to the river and landscapes, but also cultural and spiritual ties. According to such situations, omitting the justice dimensions in the claims of the greener future, it will be incomplete and may lead to conflict and project failure [64,65].

4.7. Maladaptation, Residual Risk, and Systemic Vulnerabilities

Water conservation initiatives are commonly explained as an adaptation strategy, but that can become a maladaptive strategy when it leads to a more vulnerable state in the long-run or a redistribution of risk to different populations. A good example is that of flood defenses. Levees and floodwalls may promote growth in perilous areas by decreasing the frequency of floods, exposing more people and property to destruction, in case the extreme events go beyond the design capacity. Such an effect may create an illusion of safety and cause insufficient preparation, early warning, and evacuation capability. On the same findings, supply increases that are oriented towards droughts may drive demand increases and water-intensive growth, putting systems at risk when multi-year droughts surpass system assumptions or when upstream inflows are reduced with climate change [23,66,67].

There is an aging infrastructure that presents extra systemic risk [68]. Most of the water conservancy facilities were planned for historical hydrological systems and to service loads that are no longer valid. Unscheduled maintenance may enhance the risk of failure of operation, decrease the storage capacity, and jeopardize the safety. Water systems are linked together; therefore, failures can be transmitted across sectors, including those involved in supplying electricity, agriculture, industry, and the health of the population. Also, the risk of cybersecurity and data integrity appears as the operations become more digitalized and can provide new vulnerability avenues that need to be addressed in relation to the physical risks.

4.8. Cumulative Impacts and the Problem of Scale Mismatch

One of the recurring hotspots on both environmental and social levels is the casualty of several projects in a basin. One project may sound simple; however, when combined into a network of dams, diversions, levees, and drains, hydrology, sediment transport, and ecological connectivity may change to such an extent that far exceeds the capacity of mitigation. There are also cumulative effects on the governance where various agencies and jurisdictions can operate on different aspects without coherent basin-scale goals, which contribute to fragmented accountability. Systematic underestimation of risks and overestimation of net benefits may then be generated by the mismatch of scale between the project appraisal and the basin dynamics [69].

The problem is made worse by a temporal scale mismatch [70]. Other externalities like displacement or loss of habitat are instantaneous, whereas others like erosion of deltas or storage lost during sedimentation are slow. Finance and planning systems are usually inclined to short-term benefits and underestimating long-term costs, which would structure the decision-making in favor of interventions that have a hidden cost in the future. Such an incongruity highlights the necessity of long-horizon assessment procedures and flexible governance structures that are able to react to the new pieces of evidence over the decades.

Combined, the above-discussed trade-offs are indicative of a list of priority hotspots that define whether water conservancy will make a contribution to a greener future or not [71]. The hotspots are loss of variability in flows and connectivity, discontinuity in sediments and downstream geomorphological susceptibility, loss of water quality, associated with residence time and agricultural intensification, distributive and procedural inequity, and maladaptive feedbacks leading to amplified exposure to extremes. The main lesson is that sustainability is not possible to deduce by simply looking at the type of a project. It relies on the way interventions are structured in the basin systems, the way they are realized under climate uncertainty and benefits and burdens are regulated and distributed.

This synthesis preconditions the following section by doing away with what is to be bridged in order to get net-green results. Suppose that co-benefits are conditional, and trade-offs are systemic, the central issue is to single out design, operational, and governance levers, which can cut down on these hotspots, increase adaptive capacity and achieve greater equity, and sustain vital water services. Section 5 then resorts to these levers by stressing on practical strategies and the evaluation tools, which would put the principles of sustainability into realistic avenues.

5. Bridging the Gap: Design, Operation, and Governance for Net-Green Outcomes

5.1. From Single-Purpose Assets to Multi-Objective System Design

To attain the net-green outcomes of the water conservancy projects, the conceptualization and assessment of the project should change. In the past, much intervention was optimized in a way that was dominated by a single objective: maximizing storage yield, supplying irrigation water, producing electricity, or satisfying a flood protection standard. With the modern climate and sustainability limits, such a strategy is becoming inadequate as it shifts ecological and social costs and will not work well in non-stationary extremes. The first step towards bridging the gap is thus a multi-objective design that makes the reliability of water supply, flood management, ecosystem integrity, and equity performance dimensions equal. This, in the real world, denotes considering the environmental flows, sediment continuity, and social protection as part of the basic design requirements in place of viewing them as after-the-fact mitigations. It also implies acknowledging that the most optimal solutions are usually portfolios of interventions that are spread out in a basin as opposed to a big asset, with performance being evaluated at a system level[72,73].

5.2. Engineering and Ecological Design Levers for Reducing Trade-Offs

One key cluster of levers relates to the design or retrofitting of physical structures to reduce the ecological disturbance and still be able to provide services. In this respect, environmental flow design is primary. Replacing fixed minimum flows by time-varying, seasonally fluctuating regimes that may resemble critical properties of natural variability may be more ecologically beneficial without necessarily debasing reliability, provided the additional storage is available and the allocation rules are transparent. Environmental flows can have greater effectiveness when it comes to habitat recovery and floodplain reconnection since the release of flows alone might not rehabilitate ecological processes where channels have been simplified or broken off in riparian zones[74].

Another design lever is connectivity measures, especially in regulated rivers where migration and gene flow are disrupted by barriers[75]. Fish passages, fish-friendly turbines, and bypass channels can weaken the extent of fragmentation, although their efficacy remains very species and circumstance-specific, and thus necessitates a sturdy following and refining via improvement and trial and error as opposed to installation. Simultaneously, thermal and dissolved oxygen effects of stratified reservoirs can be reduced by thermal and selective withdrawal structures and aeration technologies, which can enhance the quality of downstream habitat and decrease the complexity of water treatment.

Sediment management has become an increasingly accepted critical factor of sustainability in the long run[76]. Both downstream geomorphic collapse and loss of storage can be prevented using design strategies that can predict sedimentation and downstream sediment requirements. Sediment bypass tunnels, managed flushing, dredging with beneficial reuse, and coordinated reservoir operation to pass sediment-carrying flows are some of the options that can be used to reduce sediment discontinuity. Nonetheless, depending on the hydrology of the basin, sediment properties, the geometry of infrastructure, and the sensitivity of the downstream, these measures have varying degrees of feasibility and ecological acceptability. The bridge, in this case, is not only conceptual but also technical: sediment should be seen as an asset that is needed to withstand the current situation downstream, rather than as a mere nuisance that needs to be locked out.

Design levers applied in irrigation and conveyance systems include leakage reduction, automation of canals, measurement and control infrastructure, and upgrading of distribution networks to enhance higher scheduling precision[77]. However, the sustainability-oriented design needs to consider basin-scale water accounting, since local efficiencies can be lost in higher consumptive utilization. Therefore, the only way modernization can be justified is when it is accompanied by binding allocation constraints, environmental flow protection mechanisms, and incentives that will not lead to rebound-based growth.

5.3. Operational and Digital Levers for Adaptive Performance under Climate Uncertainty

Even properly constructed infrastructure may perform poorly when used based on strict rules that take into account stationary hydrology. One of the most short-term and scalable avenues to net-zero, and especially since much of the legacy assets in many basins are already present, is therefore operational adaptation, where new building is awkward and socially debatable. This potential can be demonstrated by forecast-informed reservoir operations. Through hydrometeorological forecasts of inflows, operators are able to change the release schedules to optimize flood buffering capacity before the storm or store more during drought risk emergence. Introduced together with clear decision guidelines and uncertainty-conscious cutoffs, these mechanisms can enhance safety and reliability and minimize the necessity of ecologically disruptive emergency releases [78].

Adaptive operations are enhanced through digital monitoring and control systems through enhanced situational awareness and dynamic optimization. Basin-scale accounting of evapotranspiration and land-use change can be supported through remote sensing, whereas in situ sensors will give real-time information regarding flows, storage, water quality, and infrastructure health. By incorporating these data streams into decision support systems, it is possible to eliminate losses, leaks can be detected, and optimize pumping schedules can be optimized; salinity and water quality risks can be dealt with in advance. Hydropower Systems Coordinated functionality has the potential to maximize the grid flexibility services and satisfy environmental flow demands to transform a potential trade-off problem into a controlled multi-objective operating problem [44,79].

Applications of optimization techniques and AI-driven tools have grown fast, with such functions as the ability to coordinate multiple reservoirs, detect anomalies, and quickly analyze scenarios. Nevertheless, the sustainability advantages of such tools require data and algorithm governance. Without incomplete or improperly implemented constraints, black-box optimization with a focus on short-term economic goals might increase inequities or environmental damage. Net-green outcomes need thus algorithmic disclosure and decision rule audit, accountability of institutions, and cybersecurity of ever more networked systems of control. Digitalization can be described as a facilitator of adaptive governance and not an alternative.

5.4. Nature-Based and Hybrid Gray–Green Pathways as a Central Bridging Strategy

Other, more sustainable alternatives to traditional infrastructure are proposed in the form of nature-based solutions (NBS) and hybrid gray-green, yet their most significant sustainability potential is often based on complementarity. Hybrid systems are aware of the fact that engineered systems may offer reliability and controllability, whereas ecosystems will offer distributed storage, filtration, habitat, and resiliency advantages unavailable to gray assets. Reconnection to floodplains, restoring wetlands, and retention landscapes can minimize peak water and enhance water quality and sustain biodiversity, and provide recreational and cultural outcomes. Urban sponge-city networks and distributed stormwater capture can lessen the runoff intensity, moderate urban heat, and enhance the water security of a locality through recharge and reuse of water [80].

Site selection, design details, and long-term maintenance are strong conditions for the performance of NBS [81]. Small restored areas that are poorly connected or those that are at high pollutant loads but lack upstream controls reduce benefits. Likewise, scaling may be limited by land competition and governance fragmentation in situations in which floodplain restoration involves land reallocation or a change in the pattern of development. Hybrid planning thus demands a portfolio view in which grey control is critical, and the green functions would provide better net benefits. Notably, the analysis of hybrid strategies should take place on a long-term basis, since most ecological advantages will be long-term as gray assets will degrade without sustenance. A plausible bridge must have monitoring systems that confirm performance, adaptive management, which can recalibrate interventions, and financing schemes that assist in long-term stewardship instead of capital investments made once.

5.5. Planning and Evaluation Tools That Translate Sustainability into Decisions

The distance between expectations and results lies in the power of the evaluation tools that can measure multi-dimensional performance and expose the trade-offs [82]. Life-cycle assessment offers a sustained platform for comparing embodied and operational emissions between alternative designs and portfolios to which is including the carbon ramifications of construction materials, energy usage, and, where applicable, greenhouse-gas emissions outlays of reservoirs. Ecosystem service assessment is a complement of LCA because it attributes value to functions (e.g., water purification, flood mitigation, habitat supply, cultural services, etc.), but non-market values and uncertainty should be carefully considered. Multi-criteria decision analysis (MCDA) provides a systematic approach to combining these dimensions and stakeholder priorities in a way that they can be transparently compared in cases where the objectives cannot be boiled down to a single dollar.

Climate change Scenario planning is also especially significant in the case of water conservancy assets because extreme-event sequences, changing seasonality, and long-term trends in inflows are sensitive to performance [83]. Decision-making techniques, stress testing, and sensitivity analysis can be used to find strategies that can do reasonably well over a broad spectrum of plausible futures, instead of being optimized to fit one particular forecast. The approach of hydro-economic modeling and system dynamics on the basin is capable of further elucidating feedbacks, including demand growth, rebounds of efficiency, and distributional impacts of the sector and community.

One of the weaknesses in the literature is the inability to compare studies and projects because of the absence of standardized sets of indicators. Bridging will necessitate improved tools as well as more regular reporting of core metrics, such as the reliability and vulnerability indexes of water supply, the performance of flood risk reduction in extremes, the sediment continuity metrics, the water quality metrics associated with health and ecological thresholds, equity and participation metrics, and carbon footprints of the life-cycle with clear system boundaries. Standardization does not mean uniformity; indicators should be flexible to context, but a common footing would enhance synthesis and lower the chances of sustainability claims being made based on cherry-picking [84].

5.6. Governance, Institutions, and Finance as Enabling Conditions

Technical plans do not suffice without the governance systems being able to implement, enact, and adapt them. The governance of basin scale is recurrently cited as one of the conditions of net-green results due to a vast number of redistributed externalities. The upstream storage and diversion impact the downstream ecosystem and livelihood; sediment entrapment impacts deltas; flood management works relocate risk; allocation decisions impact groundwater depletion and agricultural growth. Jurisdictional authorities, especially in transboundary basins, where incentives and power imbalances may result in discord, are consequently necessary. Successful governance usually involves having rules of allocation, enforceable environmental flow standards, open-minded data sharing, and participatory procedures that sensitively involve communities [85].

The focus of legitimacy and sustainability is based on equity-oriented governance mechanisms. Sharing of benefits, equitable payment, and restoring livelihoods of the displaced communities, and procedural protection to safeguard marginalized voices can minimize war and enhance long-term results. Notably, it should be substantive and not symbolic; in most cases, the processes taking place later in the planning or non-influence in decision making usually do not deal with the source of resistance. Recognitional justice is also prevalent when rivers carry cultural and spiritual significance, in which governance structures must acknowledge many systems of values and not perceive impacts as economic only [86]. **Table 4** identifies key decision questions, decision tools, data requirements, and outputs in planning, appraisal, operation, and rehabilitation to transform the review findings into reality.

Finance and maintenance regimes can either make or break the sustainability of the projects that are built [87]. The large number of failures in the performance of water conservancy is associated with insufficient funds spent on the operations and delays in maintenance, which deteriorate the level of safety and environmental results. The financial instruments that can support a sustainability-oriented portfolio are green and resilience instruments like green bonds or blended finance, though they could only be useful when monitoring indicators and protection in financing terms. Incentives to long-term performance can be harmonized by outcome-based funding, where disbursement is pegged on measured results like loss reduction, water quality improvement, or restored connection. On the same note, ecosystem services and insurance-related resiliency instruments can potentially generate revenue streams that will support green infrastructure and retention landscapes.

Table 4. Implementation toolkit for achieving net-green outcomes across the project life cycle.

Project Stage	Key Decision Question	Recommended Tools/Approaches	Minimum Data Needs	Typical Outputs
Strategic planning (basin scale)	What portfolio meets needs with lowest externalities?	Basin-scale water accounting; WEFE nexus analysis; scenario planning	Demands, inflows, allocations, ecosystems, land use	Portfolio options; trade-off frontiers; no-regret measures
Feasibility/design	How to reduce ecological/social costs while meeting service targets?	Environmental flow design; sediment continuity assessment; MCDA	Flow/sediment series; habitat/connectivity; stakeholder mapping	Multi-objective designs; mitigation packages; performance targets
Appraisal/finance	Is it net-green over the full life cycle?	LCA/LCIA; distributional analysis; avoided-damage valuation	Bill of materials; O&M plans; exposure data; social baselines	Life-cycle impacts; equity impacts; risk-adjusted benefits
Construction & commissioning	Are safeguards and performance baselines in place?	Monitoring plans; baseline ecological/social surveys	Baseline water quality/ecology; livelihood indicators	Baseline datasets; trigger thresholds; compliance systems
Operation & adaptive management	How to perform under extremes and uncertainty?	Forecast-informed operation; adaptive rules; real-time monitoring	Forecasts; telemetry; drought/flood thresholds	Updated operating rules; risk reduction; verified outcomes
Rehabilitation/retrofitting	What upgrades provide best sustainability returns?	Asset health + eco-performance audits; targeted retrofits	Condition data; performance history; downstream impacts	Retrofit roadmap; prioritized investments; O&M financing plan

5.7. A Consolidated Pathway for Net-Green Implementation

Through design, operations, and governance, a common channel is created in bridging the gap between traditional water control and sustainability transitions. The most scalable opportunities in the near term tend to be in rehabilitating the existing assets with environmental flow implementation, sediment-aware operations, reduction of leakages, and forecast-based management with better monitoring. Hybrid gray-green portfolios should also be able to increase multifunctional capacity, decrease residual risk, and increase ecosystem services, especially in the medium term when land-use planning allows the restoration of floodplain and wetlands. The long-term solution to net-green results will mean institutional adjustments to encompass basin-level caps, equitable distribution, and long-term funding of operations, maintenance, and adaptive management under climate change conditions. In this regard, bridging is not a particular act, but a paradigm of governance and design that approaches water conservancy as a stewardship of the system, which not only is capable of providing the necessary services to serve the ecosystems, climate objectives, but also can protect social equity [88,89]. **Figure 3** displays the results of the review as a step-by-step implementation roadmap separating near-term operational and retrofit opportunities, medium-term portfolio and governance transformations.

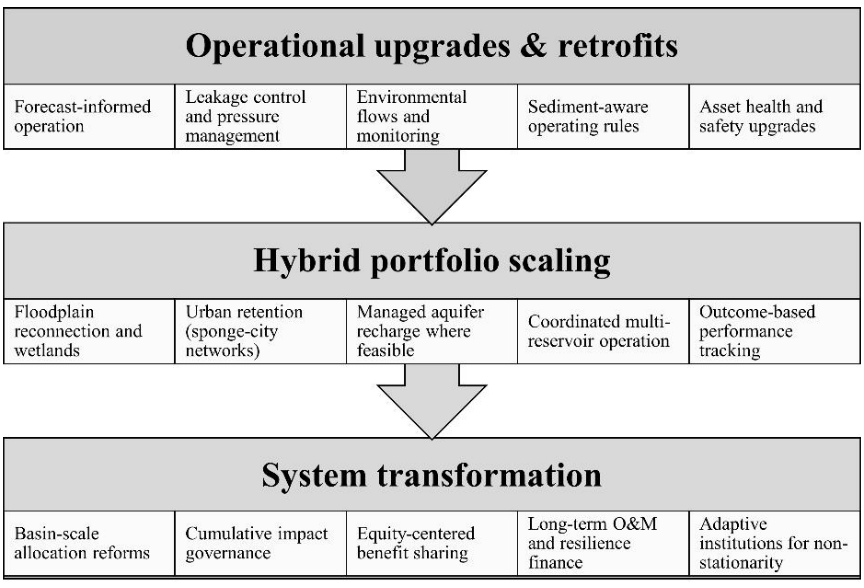

Figure 3. Implementation roadmap for net-green water conservancy under climate non-stationarity.

6. Conclusions

Conservation efforts, the water conservancy processes are beginning to be requested to perform something other than producing water, producing power, or stopping floods. They are currently tools that can facilitate a shift to sustainability under conditions of climate non-stationarity and speeding social-ecological pressures or exacerbate the situation by lock-in, cumulative degradation, and inequitable burden shifting. The evidence synthesized during this review shows that, sustainability contribution of water conservancy is not defined by the type of the project itself, but the channel through which the interventions transform basin hydrology, sediment continuity, water quality, ecosystem connectivity, and human behavior, and the institutions that control these changes over time. That is, there is production of the green result, as opposed to an assumption.

In any setting, co-benefits are the strongest when the projects enhance water security and hazard prevention without imposing downstream and future costs externalization. The storage and conveyance systems are capable of minimizing drought risks and stabilizing the urban and agricultural supply, the flood management measures would be able to minimize losses, and the capacity of the city to adapt to climate change. These advantages, however, are conditional as without basin-scale accounting, adaptive operations, and enforceable limits, the gains associated with reliability will cause an increase in demand, increase in water consumption, and increase in long-term scarcity. Similarly, the flood defenses are capable of minimizing common damages and augmenting residual risk by promoting development in open lands. The literature thus brings together a key point of the message that redefines the role of conservancy: it is neither about total control but about strong service delivery in the face of uncertainty, with limited ecological and social damages.

The ultimate deterrent to net-green results is the trade-offs. Flow regulation and fragmentation still pose risks to biodiversity and ecosystem processes; there are threats of sediment trapping, which leads to the shortening of the reservoir life-span and geomorphic resilience of the downstream; there are threats of water quality risks, which include stratification, eutrophication, and salinization through irrigation; greenhouse-gas impacts are diverse and site-dependent and system boundary dependent. The social effects, particularly the displacement, livelihoods, as well as unfair allocation of the benefits, are not marginal issues; they are the main factors that determine sustainability and the sustainability of a project. These externalities are usually cumulative and long run, and a repetitive discrepancy between project appraisal actions and the basin scale processes that eventually dominate outcomes emerges.

To address this gap, the focus of single-purpose infrastructure delivery needs to be changed to multi-objective system stewardship. The near-term opportunities are most practical in the re-operation and rehabilitation of the existing assets, where better environmental flows, sediment-conscious management, reducing leakages, and forecast-sensitive operations can bring significant profits without the extra footprint and conflict that may be a result of new construction. To boost performance, digital surveillance and decision support may be increased, but only when they are incorporated into open and responsible systems of governance that control algorithmic bias, cybersecurity, and the political economy of distribution.

Simultaneously, there is an emerging body of evidence of the increasing importance of hybrid gray-green portfolios as a viable (or practical) way to reconcile reliability and ecological integrity. The engineered structures may be supplemented with nature-based interventions like reconnecting floodplains into nature, restoring wetlands, and distributed urban retention, which reinstates natural storage, filtration, and habitat functions. Nevertheless, they rely on the site selection, scale, maintenance, and facilitating land-use governance. The hybrid strategies must then be considered as long-horizon portfolios whose performance has been demonstrated and not as Decoratives.

Lastly, governance and finance are consistently demonstrated to be conditions of enablement and not supporting policies. Coordination on a basin scale, cumulative impact evaluation, legalized environmental protection, and purposeful involvement are needed to eliminate risk transfer across the community and generations. Contemporary operations and maintenance investments are also required to maintain the same level of safety and sustainability performance as the assets wear out, and the climate becomes increasingly uncertain. Funding schemes where proven performance is used to incentivize performance - reliability, lessening losses, enhancing water quality, reinstating connectivity, and distributing benefits evenly provide a viable path towards the alignment of incentives with net-green targets.

Collectively, the results of this review allow for formulating an unambiguous suggestion: water conservation projects can form a more environmentally friendly future when they are formulated and managed as coordinated basin interventions, designed and executed to achieve multi-objective performance, and are responsible for transparent environmental and equity impacts throughout their entire life cycles. The future should be based on more standard indicators and reporting, long-term monitoring and causal assessment, better evidence of performance in terms of sediment and biodiversity, and better treatment of uncertainty and distributional effects. To practitioners and policymakers, the implication is also clear: the road to achieving green water conservancy lies not in the option between development and protection, gray and green, but through adaptive, evidence-based, and fair management of the systems on which it relies and which therefore serve human well-being and on which ecosystems rely.

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