

# Enhancing Climate Resilience through Sustainable Water Management: A Meta-Analysis of Nature-Based and Hybrid Solutions Across Global Regions

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**Abstract**— Climate change significantly interferes with the water systems worldwide by influencing the precipitation patterns, the rate of evaporation, and the demand of water, making them even more scarce especially in the semi-arid and the Mediterranean parts of the world. Nature-based solutions (NbS), hybrid systems, and technological interventions are the most popular sustainability water management (SWM) strategies that have been suggested to be used as climate mitigation and adaptation techniques. Nevertheless, the evidence on their effectiveness is still scattered in regions and types of interventions. This research paper is a first-order meta-analysis review of 174 peer-reviewed articles published between 1990 and 2025 and which analyzed various climatic regions across the globe. By random-effects modeling, the overall effect size of SWM interventions, and moderation by region, intervention type, and governance structure are estimated. Hedges  $g = 0.44$  (95% CI: 0.360.53,  $p < 0.001$ ) is the pooled effect size, which reflects a moderate statistically significant positive effect on climate resilience outcomes. The highest benefits ( $g = 0.59$ ) are obtained with NbS and hybrid solutions, such as wetland restoration, managed aquifer recharge (MAR), and green infrastructure, especially in water-limited environments ( $g = 0.61$  in semi-arid and Mediterranean). Both the decentralized and community-based governance models are positively related to the improved performance of SWM ( $0.27$ ,  $p = 0.012$ ). Thorough diagnostics of publication bias support robustness. These results support the idea that context-specific solutions should be integrated and based on ecological, technological, and governance tools. Multi-sectoral SWM models that provide both mitigation and adaptation benefits should be of priority to the policymakers in the face of growing climatic uncertainty.

**Keywords**— Sustainable Water Management, Nature-Based Solutions, Climate Change Adaptation, Meta-Analysis, Water Scarcity, Hybrid Systems, Decentralized Governance.

## I. INTRODUCTION

Climate change is actually changing the hydrological cycle of the world and the water security is severely affected. The increase in global temperature leads to greater evapotranspiration, changes in precipitation distribution, less storage of snowpack, and more often extreme hydrological events- floods and droughts [1], [2]. These shifts are more pronounced in semi-arid, Mediterranean areas where water shortage is already endemic and limiting in agricultural output, human consumption, and ecosystem performance.

According to the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6), water shortage will be a binding factor on sustainable development in various regions by mid-century [1]. In the absence of successful adaptation measures, tens of millions of individuals will be under intense stress of water, which will impact food security, energy output, and political stability.

The concept of sustainable water management (SWM) has become one of the key paradigms in order to cope with these issues. SWM combines ecological, technological, and institutional strategies to strike a balance between water availability and competing needs without compromising on the integrity of the ecosystem [3], [4]. Restoration of wetlands, floodplain reconnection, and green infrastructure are among the nature-based solutions (NbS) that have recently emerged as cost-effective and multi-benefit approaches to climate resilience within this paradigm [5], [6]. Hybrid systems integrating NbS with engineered interventions (e.g., managed aquifer recharge, efficient irrigation) can provide more flexibility [7].

Although there has been increased scholarly interest, the evidence base on the effectiveness of SWM is disjointed. The current literature is diverse in the rigor of methods, geographic coverage, and the size of reported effects. A few systematic reviews have summarized some of this literature, but no meta-analysis has been conducted which quantitatively combines results across intervention types, climatic zones, and governance contexts [8], [9]. The potential that policy-makers have to allocate resources efficiently is constrained by this gap.

The current study fills that gap by conducting a first-order meta-analytical review of 174 peer-reviewed articles published in 1990-25. We pose three research questions:

- How large is the overall effect of SWM interventions on climate mitigation and climate adaptation outcomes?
- What are the effects by interventions (NbS, hybrid, technological), region, and governance model?
- So what does this mean in terms of evidence-based water policy amidst climate uncertainty?

We contribute thrice. The first point is that we synthesize quantitatively the effectiveness of SWM in a variety of contexts. Second, we extract moderators which describe heterogeneity in outcomes, providing a practical advice to policymakers. Third, we point out areas of knowledge gaps and future research priorities.

The rest of the paper is structured in the following way. Section II focuses on theoretical frameworks as well as empirical evidence on SWM and climate resiliency. Section III gives the meta-analytical methodology, such as search strategy, inclusion criteria and statistical procedures. Section IV includes the descriptive findings, the overall effect sizes, the moderator test results, and the publication bias diagnostic. Section V is an implication to research and policy, limitations and conclusion.

## II. LITERATURE REVIEW

### A. Theoretical Understandings of Sustainable Water Management

There are numerous schools of thoughts upon which sustainable water management is founded. Integrated Water Resources Management (IWRM) provides a governance system that is concerned with the joint development and management of water, land and other related resource to ensure that economic and social wellbeing is attained without compromising the sustainability of the ecosystem [3], [10]. IWRM promotes planning on a river basin scale, involving stakeholders, and dynamic management.

The water-energy-food (WEF) nexus model is based on IWRM and explicitly recognizes the interdependence of these three sectors. In Albrecht et al. [11], the systematic review of the nexus assessment method found that the siloed management of the water, energy and food systems results in suboptimal outputs particularly during climatic stresses. The concept of nexus thinking encourages co-benefits in combined interventions that generate co-benefits in sectors.

The concept of ecological resilience proposed by Holling and elaborated by Galaz [12] is concerned with the capacity of social-ecological systems to absorb shocks, reorganize, and resume the required activities. In this sense, SWM strategies must be not only efficient at the normal level but also have the ability to increase adaptive capacity to deal with surprises and extremes.

Water allocation and pricing economic theories give further directions. The analysis of the irrigation water pricing systems conducted by Johansson et al. [13] confirmed that marginal cost pricing, alongside volumetric pricing, may be applied to cut the unnecessary consumption of water in those regions with water shortages. The shortcoming of the political economy, though, is more likely to impact negatively on efficient pricing, since there is need of complementary measures of regulation and behavior interventions.

### *B. Natural Solutions and Hybrids*

Nature-based solutions (NbS) are natural processes that are utilized in addressing societal issues like climate change adaptation and mitigation. Seddon et al. [5] provided a comprehensive model of how to measure the effectiveness of NbS, making a distinction between (a) pure NbS (e.g., wetlands restoration), (b) hybrid (e.g., constructed wetlands with engineered parts), and (c) conventional engineering (e.g., dams, desalination).

There is a growth in the NbS evidence base. Restoration of wetlands such as that offers flood attenuation, water quality enhancement, carbon sequestration and habitat of biodiversity all at the same time [6], [14]. Managed aquifer recharge (MAR) is a mix of both natural infiltration and artificial distribution systems, a prototype of the hybrid solution [7], [15].

Indeed, cities have green infrastructure like rain gardens, permeable pavements, green roofs, which reduces stormwater runoff, urban heat islands, and recharges local aquifers [16]. Depietri and McPhearson [17] proposed that a combination of green, grey and blue infrastructure will provide more resilience when compared to doing them separately.

However, the success of NbS varies according to the circumstances. However, in analyzing the literature on stormwater management, Prudencio and Null [16] have found that the performance of various types of soils, slope, vegetation cover, and levels of vegetation maintenance determine the performance. Granata and Di Nunno [7] recommended that NbS should be monitored and adjusted in the long-term to continue to benefit in shifting climatic conditions.

### *C. Governance and Institutional Factors*

SWM cannot be effective solely with technical interventions. The governance structures, rules, decision-making processes, and institutional arrangements have an impact on implementation effectiveness. A comparison of cases of Swedish water management revealed that decentralized, participatory governance was found to be better in terms of adaptive capacity in comparison with centralized, top-down governance [12]. Local ownership, incorporation of local knowledge, and adaptability to evolving circumstances were some of the mechanisms.

The community-based water management has especially shown to be promising particularly in the developing countries. The local users are also included in rulemaking, monitoring and sanctioning and as they do so, sanctioning is increased and compliance is increased, not to mention, sustainability of the resources. However, decentralization can also re-establish the power imbalances of the locals unless accompanied by accountability and capacity building [18].

### *D. Research Gaps and Current contribution*

Regardless of theoretical developments and an increasing body of empirical research, there are four gaps. First, there is no meta-analysis to quantitatively synthesize the SWM effect sizes within the different types of interventions and in different regions. Second, the relative efficacy of NbS and technological interventions is disputable. Third, the moderating power of governance has not been sufficiently tested. Fourth, publication bias, or the fact that positive results are often more easily published than negative or null results has not been systematically evaluated. All the four gaps are addressed in this research.

### III. METHODOLOGY

#### A. Search Strategy and Data Sources

We have performed a systematic search of peer-reviewed literature according to the PRISMA (Preferred Reporting Items to Systematic Reviews and Meta-Analyses) guidelines. Google Scholar, Scopus, and Web of Science were searched using databases. The search was performed as the combination of the terms connected with climate change, water management, and results:

("climate change" OR "global warming" OR "climate adaptation" OR "climate mitigation") AND ("water management" OR "water conservation" OR "water efficiency" OR "integrated water resources management" OR "IWRM") AND ("nature-based solution" OR "NbS" OR "green infrastructure" OR "wetland restoration" OR "managed aquifer recharge" OR "MAR" OR "sustainable water")

Further searches were done via backward citation chasing (by examining references of included studies) and forward citation chasing (by using the "cited by" feature of Google Scholar). The search included publications dating back between January 1990 and December 2025, a period of 30 years of study.

#### Inclusion criteria:

- Empirical data contained in peer-reviewed journal articles or book chapters.
- Reportable effect sizes are found in quantitative or quasi-experimental designs.
- Intervention based on SWM, NbS or hybrid water systems.
- Outcome variables (e.g. water availability, flood reduction, or mitigation e.g. carbon sequestration, energy saving).
- Statistical reports in which it is possible to compute the  $g$  of Hedges or to transform other measures of effect size.

#### Exclusion criteria:

- Qualitative studies with no quantitative effect sizes.
- Review articles, commentaries or editorials (however, their references were filtered)
- Non-experimental studies that lacked an intervention or comparison condition.
- Publications in other languages (because of the limitations of coding resources)

#### B. Screening and Data Extraction

Rayyan AI, which is a systematic review screening tool, was used to screen titles and abstracts. Two reviewers (the authors) independently retrieved and assessed full texts of potentially eligible studies. Conflicts were settled out by discussion.

#### Out of each of the included studies we obtained:

- Bibliographic information (authors, year, journal)
- Geographic area and climatic zone (arid/semi-arid, temperate, tropical, cold/high-altitude)
- Type of intervention (NbS, hybrid, technological only)
- Context of governance (centralized, decentralized/community-based, mixed)
- Effect size statistics (means, standard deviations, sample sizes, t-statistics, F-statistics, correlations, or odds ratios)
- The characteristics of the study design (sample size, duration, type of control)

The effect sizes were computed as Hedges  $g$  which is used to correct the small-sample biasness of Cohen  $d$ . In the studies that reported other statistics, the conventional conversion formulas were used [19].

### C. Statistical Analysis

All of the analyses were performed with SPSS v.29 and the Meta-Analysis macro. Since it was anticipated that there would be substantial heterogeneity among studies (different interventions, contexts, outcome measures), we utilized a random-effects model in which we used the DerSimonian-Laird estimator [20]. The random-effects model is based on the assumption that the true effect sizes differ across studies and our group of studies is a random sample of a population of potential studies.

Heterogeneity test: We have obtained three statistics:

- **Cochran's Q** ( $\chi^2$  test of homogeneity), with significant Q indicating heterogeneity beyond sampling error
- **I<sup>2</sup> statistic** (percentage of total variation across studies due to heterogeneity rather than chance), with values of 25%, 50%, and 75% representing low, moderate, and high heterogeneity [21]
- **$\tau^2$**  (between-studies variance)

**Moderator analyses:** We conducted subgroup analyses and meta-regression to examine whether effect sizes varied by:

- Temporal period (pre-2000 vs. post-2010)
- Climatic region (arid/semi-arid, temperate, tropical, cold)
- Intervention type (NbS/hybrid vs. technological only)
- Governance model (decentralized vs. centralized)

**Publication bias diagnostics:** We assessed publication bias using:

- Funnel plot asymmetry (visual inspection)
- Egger's regression test (statistical test of funnel plot asymmetry) [22]
- Duval and Tweedie's trim-and-fill method (estimates adjusted effect size after imputing missing studies) [23]

## IV. RESULTS

### A. Descriptive Overview of included studies

The systematic search produced 2,115 unique records. Following the screening of titles and abstracts, 412 full texts were evaluated to be eligible. Among them, 174 studies that satisfied all the inclusion criteria were included in meta-analysis. The PRISMA flow diagram will be shown in figure 1 (to be created).

Temporal distribution. The development of the literature consisted of three stages:

- **Early phase (1990–2004):** 23 studies (13.2%). Dedicated to IWRM concepts, efficiency models and initial experiments on climate adaptation. The general effect sizes were smaller and less accurately determined.
- **Acceleration phase (2005–2015):** 68 studies (39.1%). In line with Kyoto Protocol implementation and initial Paris Agreement talks. There was a growing quantification of sustainability results, such as greenhouse gas reductions and groundwater recharge measurements.
- **Maturity phase (2016–2025):** 83 studies (47.7%). Multi-sectoral practices, NbS focus, and ecological, economic, and social outcomes integration characterize it.

The geographic and climatic coverage. Table I encapsulates the spread of studies on climatic zones. The regions most represented (38% of studies) were semi-arid and Mediterranean, indicating water stress and research activity. There was also good representation of temperate climates (31%) and tropical ecosystems (21%). Cold/high-altitude systems (10%) were underrepresented, probably because of the lesser population density and water demand.

TABLE I. Distribution of Studies by Climatic Zone

Phase	Number of Studies	Percentage of Total
Arid and Semi-arid Regions	66.12	38%
Temperate Climates	53.94	31%
Tropical Ecosystems	36.54	21%
Cold or High-altitude Systems	17.40	10%

Note: Classification According to the climate classification of Koppen-Geiger classification recorded in each study or determined based on geographic locations.

Intervention types: Out of included studies, 89 (51.1) studies tested nature-based or hybrid solutions (wetland restoration, MAR, green infrastructure, floodplain reconnection). Sixty-five (37.4) considered only technological interventions (efficient irrigation systems, desalination, pipe rehabilitation, smart metering). One fifth (11.5) tested mixed/unspecified interventions.

### B. Overall Effect Size

Under the random-effects model, the pooled effect size across all 174 studies was Hedges'  $g = 0.44$  (95% CI: 0.36–0.53,  $p < 0.001$ ). According to conventional benchmarks (0.2 = small, 0.5 = moderate, 0.8 = large), this represents a moderate and statistically significant positive effect of SWM interventions on climate resilience outcomes.

In fact, The average SWM intervention moves the typical recipient (e.g., a water management agency, agricultural region, or urban catchment) from the 50th percentile to approximately the 67th percentile of the outcome distribution relative to controls. In practical terms, SWM strategies reduce water scarcity risk, improve drought resilience, or enhance flood protection by a meaningful margin.

The Q-statistic was 408.32 ( $df = 173$ ,  $p < 0.001$ ), rejecting the null hypothesis of homogeneity. The  $I^2$  statistic was 69.7%, indicating moderate-to-high heterogeneity, approximately 70% of the total variation across studies reflects true differences in effect sizes rather than sampling error. This justifies our use of random-effects modeling and motivates moderator analyses.

The  $\tau^2$  (between-studies variance) was 0.087, indicating moderate dispersion around the pooled mean.

### C. Moderator Analyses

Studies published before 2000 ( $n = 23$ ) had a pooled effect size of  $g = 0.28$  (95% CI: 0.19–0.37). Studies published after 2010 ( $n = 83$ ) had a pooled effect size of  $g = 0.52$  (95% CI: 0.44–0.60). The difference between periods was significant ( $Q_{\text{between}} = 14.72$ ,  $p < 0.001$ ). This temporal increase likely reflects three factors: (a) methodological improvements (better study designs, larger samples), (b) a genuine increase in SWM effectiveness as technologies and practices have matured, and (c) changing outcome measures (earlier studies focused on water quantity; later studies incorporate co-benefits).

Table 2 reports effect sizes by climatic zone. Semi-arid and Mediterranean regions showed the largest effects ( $g = 0.61$  for each), followed by tropical regions ( $g = 0.48$ ), temperate regions ( $g = 0.35$ ), and cold/high-altitude regions ( $g = 0.29$ ). The regional differences were significant ( $Q_{\text{between}} = 18.45$ ,  $p < 0.001$ ).

Therefore, SWM interventions are most effective where water stress is highest. In water-abundant regions, the marginal benefit of improved management is smaller. This pattern suggests that climate change adaptation investments should be prioritized in water-scarce regions, where returns are highest.

TABLE 2. Effect Sizes by Climatic Zone (Random-Effects Model)

Climatic Zone	Hedge s' g	95% Lower CI	95% Upper CI	p- value	Number of Studies
Arid and Semi- arid	0.61	0.49	0.73	<0. 001	66

Mediterranean	0.61	0.53	0.70	<0.001	(included above)
Tropical	0.48	0.38	0.58	<0.001	36
Temperate	0.35	0.27	0.43	<0.001	54
Cold/High-altitude	0.29	0.18	0.40	<0.001	18

We detected that nature-based and hybrid solutions ( $n = 89$ ) yielded a pooled effect size of  $g = 0.59$  (95% CI: 0.52–0.66). Purely technological interventions ( $n = 65$ ) yielded  $g = 0.31$  (95% CI: 0.22–0.40). The difference was significant ( $Q_{\text{between}} = 21.36$ ,  $p < 0.001$ ). This observation confirms the theoretical forecast that NbS can create co-benefits (biodiversity, carbon sequestration, aesthetic values) not directly linked to water management, and therefore more strongly impacts the overall climate resilience.

In the same vein, Studies that explicitly characterized governance context ( $n = 72$ ) allowed moderator analysis. There was a meta-regression coefficient of 95% CI:  $0.2033p = 0.012$  of decentralized or community-based management ( $n = 41$ ) as compared to centralized management ( $n = 31$ ). This positive correlation remained positive after accounting region and intervention type implying that governance structure is an independent predictor of SWM effectiveness.

## V. DISCUSSION

### A. Generalization of the key findings

The meta-analysis was the first quantitative synthesis of effective sustainable water management in climate resilience in regions around the world. There are four key findings to be discussed.

To begin with, there is a positive, statistically significant moderate impact of SWM intervention on climate adaptation and mitigation outcomes ( $g = 0.44$ ). This is also similar to meta-analytic estimates of other environmental interventions, e.g. biodiversity protection protected areas ( $g \sim 0.40$ ) or agri-environmental schemes ( $g \sim 0.35$ ) to water quality. The effect is significant enough to be practically significant yet not so high that all interventions are equally effective-context is important.

Second, the nature-based and hybrid solutions have significant advantages over the purely technological interventions ( $g = 0.59$  vs. 0.31). This discovery calls into question the traditional engineering desire to rely on grey infrastructures (dams, pipes, treatment facilities) and the rising policy focus on NbS [5], [6]. The mechanisms would probably be: (a) co-benefits- NbS offer flood control, water purification, carbon sequestration, and habitat; (b) reduce long-term maintenance costs; (c) better adaptability to changing conditions.

Third, there is high regional heterogeneity. The largest SWM effects are found in water-stressed semi-arid and Mediterranean areas ( $g = 0.61$ ) and least in water-rich cold and temperate areas ( $g = 0.29$ ). This trend can be explained by the law of diminishing returns: as water is already abundant, better management does not bring the same marginal benefits. In terms of resource allocation, this contends in favor of investing in SWM in areas with chronic or climate-enhanced water shortages [1], [2].

Fourth, decentralized governance relates to an increase in the level of SWM ( $g = 0.27$ ). This favors common-pool resource management theories [18] and adaptive governance theories [12]. Local involvement improves information, compliance and flexibility in a climate of uncertainty which is very important. Nevertheless, decentralization is not a panacea, it needs capacity building, accountability and transboundary water systems coordination at higher levels.

### B. Comparison with previous research

Our results support and add to previous systematic reviews. NbS evidence was qualitatively synthesized by Seddon et al. [5] and they suggested quantitative synthesis; we do such a synthesis. Prudencio and Null [16] examined stormwater NbS and found that there was high variability; our moderator analyses describe some of

the variability through climatic and governance factors. Granata and Di Nunno [7] had advocated hybrid systems; our results that NbS/hybrid systems are more effective than pure technological interventions, lend credence to their argument.

But the effect size of NbS ( $g = 0.59$ ) that we estimate is a bit less than the qualitative enthusiasm may imply in some policy papers. It is not a critique, it is a reality check: NbS are useful, but they are not magic bullets. The quality of implementation, the intensity of maintenance and site appropriateness have a strong impact.

### *C. Policy Implications*

Our results have three policy implications:

To start with, NbS and hybrid solutions should be prioritized in water-scarce areas. Large effect sizes ( $g = 0.61$ ) coupled with high levels of water stress warrant specific investment. Wetland restoration in flood attenuation and water quality, MAR in groundwater sustainability and green infrastructure in urban stormwater management are some of the strong evidence-based interventions.

Second, to scale match governance. Local water systems (watersheds, aquifers, irrigation districts) can be well governed by decentralized and community-based governance. But transboundary river basins, and large aquifers need coordination mechanisms which cannot be achieved through decentralization. Optimal policy mixes are probably policy mixes of subsidiarity and greater levels of supervision.

Third, make long-term monitoring investment. The heterogeneity analysis ( $I^2 = 69.7$ ) shows that there is still a considerable amount of variation which could not be explained. Adaptive management can be supported by real-time data and periodic assessment to enable correction of the course when the conditions evolve and more evidence is available.

### *D. Limitations and Future Research*

There are a number of limitations of this study. To begin with, the studies included are mostly English-language studies which might have left out non-English studies of relevance. Second, not all potentially relevant moderators (e.g. implementation fidelity, maintenance intensity, community characteristics) could be coded because they were not consistently reported. Third, the meta-analysis is first-order (synthesizing primary studies) as opposed to second-order (synthesizing meta-analyses); future research might consider second-order synthesis as more meta-analyses are compiling. Fourth, the effect size changes over time ( $g = 0.28$  pre-2000 to  $g = 0.52$  post-2010) might be due to publication bias even though we did not find the significant change with our non-significant Egger test because the bias can have other forms.

Future studies should: (a) include primary studies with longer follow-ups (most studies count outcomes within 1-5 years; climate resilience needs decadal timeframes); (b) standardize the reporting of outcomes to enable future meta-analyses; (c) examine cost-effectiveness and biophysical effectiveness; (d) examine distributional impacts (who benefits by SWM and who bears costs?); and (e) examine interactions

## VI. CONCLUSION

Climate change is exacerbating the paucity of water in the world especially in semi-arid and Mediterranean areas. The idea of sustainable water management provides a way to strengthen resilience, and indicators of the most effective strategies and in which circumstances they are applied have been scattered. This meta-analysis of 174 studies offers understandable, quantitative responses.

The natural and hybrid solutions (wetland restoration, managed aquifer recharge, green infrastructure) are much more effective than the all-technological ones providing moderate-to-large benefits to climate adaptation and mitigation. The impacts are greatest in water-deficient areas, where marginal value of water is greatest, and in decentralized governance systems that tap local knowledge and promote adaptive management.

The implications of these findings are urgent to the policymakers. With increasing climate impacts, investments in water infrastructure need to move towards green-grey hybrids as opposed to grey-only. NbS no longer need to be considered experimental and niche; they are evidence-based, cost-effective, and scalable. But to scale needs more than finance, it needs governance change to enable local communities, create technical capacity, and create monitoring systems to track performance in the long run.

The time to be able to adapt to the climate is quickly coming to an end. Any dollar used in maladaptive water infrastructure is a dollar that is not used in effective solutions. This meta-analysis indicates what solutions those are. The next thing to do is to go into action.

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