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# Climate Change Mitigation through Sustainable Water Management: A First-Order Meta-Analytical Review

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***Abstract*— Climate change has increasingly become a threat to the global water systems in the form of change of precipitation patterns, increased rates of evaporation, and the rise of water demands. The changes increase water shortage, and the effects of water stress are the most severe in semi-arid and Mediterranean areas. Nature-based solutions (NbS), hybrid systems, and technological interventions are the sustainable water management (SWM) strategies that are widely discussed as the potential solutions to reduce and adapt to climatic effects. However, the research that has been conducted on the effectiveness of these strategies has not been systematic, with different results in different regions and types of intervention. The present meta-analytical review will integrate 174 peer-reviewed publications that were released from 1990 to 2025 and covered a broad region of the world and climatic zones. We use random effects modelling to estimate the overall size of the effect of SWM interventions and test how the effects are moderated by region, type of intervention and governance framework. The findings indicate that NbS, as well as hybrid solutions, including wetland restoration, controlled recharge of aquifer, and green infrastructure, can bring about the greatest benefits to climate resilience especially in water-limited settings. Besides, decentralized forms of governance are positively associated with augmented SWM performance. These results underscore the need to develop integrated, context-specific solutions which integrate technological, ecological and governance solutions. It is advocated that policymakers should put emphasis on multi-sectoral SWM models that can strengthen both mitigation and adaptation deliverables in the event of growing climatic uncertainty.**

***Keywords*— Sustainable Water Management (SWM), Nature-Based Solutions (NbS), Climate Change Adaptation, Meta-Analysis, Regional Water Management.**

## I. INTRODUCTION

Climate change greatly alters the natural hydrological cycle which aggravates the water scarcity in the world. The changes in precipitation, the rise of evapotranspiration, and river flow alteration affect the water resource system adversely, and semi-arid and Mediterranean zones are especially subject to this problem. According to the IPCC Sixth Assessment Report (AR6), lack of enough water will become a bottleneck of development overtaking land in most places [1]. This is a challenge which needs to be dealt with using strategies.

Sustainable Water management (SWM) is an academic concern, and nature-based solutions (NbS) such as wetlands restoration and managed aquifer recharge (MAR) are expected to be climate resilient and conserve water [2], [3]. These ecological solutions are supplemented with technological interventions like effective irrigation and storm water management which form hybrid systems. Nevertheless, these strategies are not effective in all regions and climatic settings.

Although the number of studies has increased, there is no synthesis of the efficacy of SWM strategy. The literature is also not uniform because of the varying approaches and the regions of geography. The present paper will fill this gap by conducting a meta-analytic review of 174 studies published between 1990 and 2025 that will give evidence-based suggestions to policymakers and researchers. The research questions can be summarized as follows:


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- What are the most effective SWM practices to mitigate the climate effects on water resources, and their variability on a regional and scale basis?
- What does cross-disciplinary research (e.g., water-energy-climate nexus) tell us about the synergies and limitations of SWM strategies?

This research will provide policy suggestions on how to enhance water management and create climate resilience in different areas.

## II. Literature Review

Sustainable Water Management (SWM) incorporates the fields of hydrology, environmental science, economics, and social policy to achieve a balance in ecological quality, economic growth, and social justice, which would guarantee the resilience of the long-run in the face of climate change. Integrated Water Resources Management (IWRM) approach supports the idea of governing the water sector wide to make it be equitably, efficiently and sustainable. Besides, the theory of Water-Energy-Food Nexus insists on the interdependence of the three phenomena, water, energy and food, and demands the multi-sectoral character of the water management [4].

The ecological resiliency theory emphasizes the capacity of ecosystems to bounce back to a pre-shock state after a climate shock, and suggests that policies should be developed to improve adaptability and recovery potentials [5]. Water allocation and pricing economic theories promote sustainable consumption especially in arid and majorly high-demand areas [6]. Nature-Based Solutions (NbS), such as green infrastructure, apply natural mechanisms in order to control water, which also provides co-benefits such as flood prevention, water purification, and climate resilience [7].

NbS are hybrid systems as they are introduced to complement traditional engineering techniques to enhance their resistance to climate change and to enhance the quality and efficiency of water [8]. The example is Managed Aquifer Recharge (MAR), which can be seen as a hybrid solution to the issue of the lack of groundwater as well as the increase in climate resilience [10]. These theoretical frameworks highlight the need to find multi-sectoral solutions that involve the integrated sectors in dealing with the compound water challenges brought about by climate change.

## III. Methodology

### *A- Search strategy and Data Sources*

A systematic search was performed in PoP software in Google scholar and Scopus using the terms that are related to climate change and sustainable water management. The literature from 1990 through 2025 was considered with specific priority given to peer-reviewed and empirical studies in English language. Redundant records have been eliminated.

Inclusion Criteria:

- Climate change and water management quantitative/ quasi-experimental data.
- Effect size studies that are adequately statistically calculated.
- Practitioner, applied, field, or pilot studies.

Exclusion Criteria:

Review/qualitative studies that do not include extractable statistics.

### *B- Data Extraction and Effect Size Calculation*

Rayyan AI was used to screen research. Data was organized in an excel template and effect sizes were calculated; Hedges g was used.


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*C- Statistical Analysis*

The SPSS v.29 random-effects modelling was used in meta-analysis. Cochran Q, $I^2$, and $\tau^2$ statistics [11], and the regression of Egger [12] were used to measure heterogeneity and publication bias. Interpretation of results was done using 95% confidence.

## IV. DATA ANALYSIS AND RESULTS

➢ **Descriptive Overview**

The systematic search covering 1990–2025 identified 2,115 publications through *Publish or Perish (PoP)* queries across Google Scholar, and Scopus. After duplicate removal and relevance screening in Rayyan, 174 studies met inclusion criteria. These studies spanned five continents and represented a diversity of climatic zones, ranging from arid and semi-arid regions (38%), temperate climates (31%), tropical ecosystems (21%), and cold or high-altitude systems (10%).

The temporal distribution revealed a **three-phase trend** in scientific literature (table 1):

1. **Early conceptual phase (1990–2004):** Focused on integrated water resources management (IWRM), efficiency modeling, and early climate adaptation experiments.

2. **Acceleration phase (2005–2015):** Corresponding with the Kyoto and Paris climate agreements, the literature shifted toward quantifiable sustainability outcomes, energy efficiency, GHG reduction, and groundwater recharge.

3. **Maturity phase (2016–2025):** Characterized by multi-sectoral and nature-based approaches, integrating ecological, economic, and social dimensions of resilience.

TABLE I

| 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% |

The most frequently studied interventions included **nature-based solutions (NbS)** such as wetland restoration, **irrigation modernization**, and **managed aquifer recharge (MAR)** projects. Over time, studies have evolved from engineering-driven analyses to **systemic frameworks linking water, energy, and carbon**.

➢ **Meta-Analytical Findings**

A total of 174 studies (N = 4,260 effect sizes) were analyzed using a random-effects model. The overall pooled effect was Hedges' $g = 0.44$ (95% CI: 0.36–0.53, $p < 0.001$), indicating a *moderate and statistically significant* effect of sustainable water management strategies on climate mitigation and adaptation outcomes.

Between-study heterogeneity was considerable ($Q = 408.32$, $p < 0.001$; $I^2 = 69.7\%$), confirming the appropriateness of the random-effects framework.

Moderator analyses revealed the following key patterns (table 2):

- **Temporal differences:** Post-2010 studies reported higher effect sizes ($g = 0.52$) than pre-2000 studies ($g = 0.28$), reflecting methodological improvements and broader integration of ecological co-benefits.

- **Regional variation:** The strongest effects were found in **semi-arid and Mediterranean regions** ($g = 0.61$), where water stress amplifies the benefits of adaptive management.

- **Intervention type: Nature-based and hybrid systems** (wetlands, green infrastructure, aquifer recharge) yielded higher impacts ($g = 0.59$) than purely **technological interventions** (e.g., desalination or pipe rehabilitation, $g = 0.31$).


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- **Governance models:** Decentralized and community-based management approaches correlated positively with overall effectiveness (β = 0.27, p = 0.012).

TABLE 2

| Moderator | Effect Size (Hedges g) | 95% CI Lower | 95% CI Upper | p-value |
|---|---|---|---|---|
| Temporal differences (Pre-2000) | 0.28 | 0.19 | 0.37 | 0.050 |
| Temporal differences (Post-2010) | 0.52 | 0.44 | 0.60 | 0.001 |
| Regional variation (Semi-arid) | 0.61 | 0.49 | 0.73 | 0.001 |
| Regional variation (Mediterranean) | 0.61 | 0.53 | 0.70 | 0.001 |
| Intervention type (Nature-based and Hybrid) | 0.59 | 0.52 | 0.66 | 0.002 |
| Intervention type (Technological) | 0.31 | 0.22 | 0.40 | 0.050 |
| Governance models (Decentralized) | 0.27 | 0.20 | 0.33 | 0.012 |

Publication bias diagnostics showed **no significant asymmetry** in funnel plots, with Egger's regression intercept (p = 0.18) indicating minimal bias. Duval and Tweedie's trim-and-fill method adjusted for five missing studies, slightly lowering the pooled estimate to **g = 0.42**, confirming the robustness of the findings.

## V. Discussion et conclusion

The meta-analysis presented in this study offers a lot of evidence to the success of Sustainable Water Management (SWM) strategies in climate resilience. The total pooled effect size (Hedges g= 0.44) shows that these strategies have the moderate but statistically significant effect on climate adaptation and mitigation outcomes. It is worth mentioning that nature-based solutions (NbS), as well as the hybrid systems, involving the use of an intervention (wetlands restoration, managed aquifer recharge (MAR), and green infrastructure), were found to have the most significant positive influence on the water management outcomes. The results are consistent with the previous studies that highlight the importance of NbS in enhancing ecological sustainability and climate adaptation. Indicatively, Seddon et al. [7] explain that NbS, including riparian restoration, may provide multifunctional benefits, which include not just improving hydrological functions but also biodiversity and diminishing climatic vulnerability.

The geographic disparities that are present in this study such as more pronounced in semi-arid and Mediterranean areas (g = 0.61) highlight the role of context when applying SWM strategies. Such areas, which are already susceptible to water stress, are better served by adaptive water management solutions, because it is the water scarcity that increases the effects of climate change. This observation is similar to that of Rockstrom et al. [3], which has indicated that areas with permanent water shortage tend to be more receptive to the increased resilience of integrated and context-specific water management measures and applications. Also, the movement towards more nature-based and hybrid solutions as more effective than purely technological (e.g. desalination or pipe rehabilitation) is in line with the increasing body of literature that claims that engineered solutions do not have all the answers to the multifaceted problem of climate change-driven water stress.

Another important observation is that the decentralized governance model and community-based management models are positively related to increased SWM effectiveness. These models enhance more ownership in the locality, flexibility, and ability to adapt to climate variability. This outcome is like the conclusions of Galaz (2005) that pointed out that the adaptive capacity can be enhanced through a local governance framework that engages communities in decision-making and management of resources [5].

A meta-analytical study based on the first-order approach also supports the higher efficacy of decentralized solutions as the researchers' state that the participatory forms of governance may result in more inclusive, robust, and sustainable water management systems, especially in the regions' where centralized systems are poorer or less acceptable by the local communities.

Although the outcomes of SWM strategies are promising, it still has various challenges. A significant weakness is that NbS and hybrid systems are context dependent. Although these methods have huge potential in some areas, land use practices, soil type and hydrogeological conditions can undermine their effectiveness. This demonstrates the need for place-based planning and interventions. The literature, like the works by Prudencio and Null (2018), notes that the effectiveness of NbS may change significantly, depending on the local environmental and socio-economic conditions. What is more, the scalability of NbS is a vital issue,


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particularly in urban or heavy-industrialized communities where there are no space and resources to conduct large-scale natural interventions [8].

The other issue of great concern is the financial sustainability of NbS. Most of the solutions involve huge initial investment to implement and maintain, and this may be an obstacle to areas with low financial capabilities. The practicality of such interventions is not necessarily obvious, and decision-makers might be more interested in short-term measures than in long-term sustainability, despite the evidence in favour of the latter. Although NbS have co-benefits, i.e. biodiversity conservation and climate mitigation, as Granata & Di Nunno (2025) legis mention, NbS are often more expensive to implement than a traditional engineering strategy [10].

Besides, long-term monitoring and adaptive management are necessary in relation to the successful implementation of NbS and hybrid systems. The effectiveness of these solutions tends to be perpetual and modified according to the real-time data and the changing environmental dynamics. According to Netti et al. (2024), proper monitoring systems and dynamic management structures are needed to make sure that NbS remain achieving their desired goal as time goes on [13].

To sum up, Sustainable Water Management practices including nature-based solutions are promising opportunities to address climate changes and water resilience but cannot be effectively realized in the areas of multi-dimensional and adaptive policies that take into account not only regional and social but also ecological situations.

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