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Effectiveness of Ecosystem-based Adaptation in South Africa's freshwater ecosystems: A systematic review

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A R T I C L E I N F O

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A B S T R A C T

Ecosystem-based Adaptation (EbA) has gained significant traction in South Africa over the past decade as a preferred strategy for enhancing climate resilience through the sustainable management of ecosystems. However, empirical evidence demonstrating the effectiveness of EbA within freshwater ecosystems remains limited. We systematically review peer-reviewed literature (*n=27*) to assess the effectiveness of EbA interventions for both people and ecosystems, and to identify critical knowledge gaps that constrain effective EbA implementation. The review indicates that EbA interventions generally contribute to measurable improvements in ecosystem services across multiple freshwater ecosystem types such as streamflow regulation and biodiversity maintenance. Nonetheless, several studies report unintended negative outcomes arising from poorly designed or implemented interventions. Evidence on socio-economic benefits remains sparse, and where such benefits are documented, they are often short-term or temporary, such as limited-duration employment. Literature that directly links EbA interventions to specific climate hazards is also scarce, with many studies requiring inferred relationships rather than providing explicit causal evidence. Furthermore, there is a notable lack of studies evaluating the economic viability and cost-effectiveness of EbA relative to alternative adaptation strategies. Our findings highlight the need for more robust, long-term, and interdisciplinary research to strengthen the evidence base for EbA in South Africa's freshwater ecosystems.

1. Introduction

Southern Africa is characterised by a warm climate and distinct wet-dry seasonal patterns. It is a water-stressed region due to low mean rainfall and frequent occurrence of naturally induced droughts [1]. Observational records and climate projections consistently indicate that Southern Africa is likely to become substantially warmer and generally drier, with increased extremes, in the coming decades [2]. Freshwater ecosystems are among the most vulnerable to climate change impacts owing to their high sensitivity to hydrological and temperature shifts [3]. In semi-arid regions like South Africa, where freshwater availability is already critically limited, climate projections indicate further reductions from increased multi-year droughts and intense rainfall events separated by longer dry spells [2,4]. These changes are expected to negatively affect multiple components of freshwater ecosystems, including water quantity, quality, physical habitat, and aquatic biological assemblages [5,3]. Such impacts threaten the continued delivery of essential ecosystem services, making well designed adaptive responses to reduce climate vulnerability especially urgent given South Africa's pressing socio-economic development needs [6,7].

Adaptation to climate change is necessary as the impacts of climate change become more frequent and intense [8]. Functioning ecosystems help people to adapt to climate change [9], including reducing the risk of climate extremes [10]. Despite numerous ways to adapt to climate change, Ecosystem-based Adaptation (EbA) uses ecosystems to help people cope with climate change and is often associated with the term Nature-based Solutions (NbS) for climate change adaptation despite NbS being the broader umbrella concept that includes EbA among many other nature related strategies [11,12]. EbA has gained increasing attention over the last two decades as a suitable approach to climate change adaptation [13]. EbA integrates the sustainable use of biodiversity and ecosystem services to help people adapt and build resilience to the adverse effects of climate change as part of an overall adaptation strategy [14,15]. It relies on the protection and restoration of ecosystems to reduce the vulnerability of societies to stresses associated with climate change, while maintaining or increasing the resilience of

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social–ecological systems to the pressures of climate risks [16]. Central to EbA is a people-centric participatory, inclusive, and transparent approach that recognises the interdependence between ecosystem integrity and human well-being, ensuring that interventions are socially just and contextually appropriate [17,18]. Furthermore, EbA principles indicate that EbA must be grounded in the best available science, drawing on both robust empirical evidence and the rich insights of indigenous and local knowledge systems to inform design, implementation, and evaluation [11,19].

EbA implementation in South Africa is currently guided by the National Strategic Framework and Overarching Implementation Plan of 2016-2021 [15], the EbA Guidelines of 2018 [19] and the EbA Action Plan and Priority Mapping of 2020 [20]. These have created a strong enabling environment and provided environmental safeguards against mal adaptation. This provides a positive platform to encourage action across multiple governance levels in the country especially with a new draft of the EbA strategic plan for 2025–2034 underway [21]. The EbA strategy and related tools aimed to mainstream EbA into climate change and biodiversity initiatives across the country, building on existing efforts and integrating EbA principles into local, provincial, and national development planning levels [15]. For centuries, people have been managing the environment and adapting in response to climate risk. For example, in South Africa, there have been multiple interventions that coupled employment through green jobs with restoring landscapes and protecting water sources ([22], Table 4). So, although these interventions are not explicitly labelled as EbA, they are relevant [23].

Although EbA has gained significant traction in South Africa over the past decade as a cost-effective and promising nature-based response to climate change [24], a critical gap remains in understanding its effectiveness within the context of freshwater ecosystems. There is limited availability of empirical, context-specific evidence that evaluates the outcomes of EbA interventions in South African freshwater ecosystems [25]. To date, most efforts to consolidate evidence on EbA effectiveness have taken the form of global reviews (e.g. [26,8,23]), which include only a handful of South African case studies. As a result, these global syntheses provide only partial insight into how EbA functions in the unique socio-ecological settings of South Africa's freshwater systems, leaving decision-makers and practitioners with insufficient data to guide policy, investment, and implementation. Systematic evidence on EbA, therefore, needs to be strengthened [27]. According to Reid *et al.* [28], assessing the effectiveness of EbA is crucial due to several interrelated challenges that hinder its widespread and sustained implementation. These include ongoing uncertainty about how to finance EbA interventions in a locally sustainable and long-term manner, as well as the mismatch between the long-term impacts of climate change and the short-term nature of political cycles and decision-making processes. Compounding these issues is the limited evidence base regarding the overall effectiveness of EbA, particularly in terms of its economic viability, which further constrains policy uptake and investment. Evaluating effectiveness is essential to build an evidence base that clarifies the factors driving success, identifies gaps, and informs future research and policy. In this review paper we systematically synthesise scientific evidence on the effectiveness of EbA interventions for people and ecosystems across South African freshwater ecosystems; and identify key research gaps and knowledge limitations that constrain the design, implementation, and scaling of effective EbA strategies.

2. Methods

We used a two-phase approach to assess the effectiveness of EbA interventions in freshwater ecosystems across South Africa. The first phase involved the development of an assessment framework (Table 1) to evaluate the ecological and social outcomes of EbA interventions. This framework drew on existing EbA principles and effectiveness criteria, incorporating aspects such as reductions in climate vulnerability, improvements in ecosystem service delivery, and potential co-benefits for biodiversity and local livelihoods [15,29].

In the second phase, we conducted a systematic literature review guided by this framework. The review focused on peer-reviewed literature that reported on freshwater-related interventions relevant to EbA across South Africa. Clearly defined inclusion and exclusion criteria were applied to identify studies that linked ecosystem interventions with climate adaptation outcomes for ecosystems and people. Many relevant interventions are not explicitly labelled as EbA, such as those described by Munroe *et al.* [23], which include restoration, water and soil conservation, but were included if they were implicitly linked to reducing

Table 1
Modified EbA assessment framework adapted from [29].

1. ***Effectiveness for Human societies***

★ Did the EbA intervention reduce the socio-economic vulnerability of the people and communities in the face of climate change?

- Did the intervention provide employment for the local communities? If so, over what timeframes was this benefit felt?
- Which groups benefited from EbA interventions? (Did vulnerable groups benefit?)
- Did the intervention improve access to essential resources like water? (thereby reducing sensitivity to climate change and buffering against climate extremes)
- Did the intervention have a positive impact on the livelihoods of local communities around the freshwater ecosystem? (thereby reducing economic sensitivity to climate variability)
- Was the community actively involved in the intervention planning, implementation, monitoring, and building ownership?
- Did the intervention lead to any other social benefits? (Did the intervention improve the quality of life in any way e.g. improve access to water, increased food security, reduced health risks, disaster risk reduction, livelihood diversification, reduction in conflict over scarce resources?)
- Did the intervention lead to other sustainable income opportunities, such as ecotourism or fishing, due to improved ecosystem health?
- Did community members around the ecosystem receive training or skills, or new knowledge to reduce sensitivity to climate impacts?
- Was there any responsibility by locals for ongoing maintenance and protection?

2. ***Effectiveness for the Ecosystem***

★ Did the EbA intervention reduce ecological vulnerability of the freshwater ecosystem through either restoring, maintaining or enhancing the capacity of the ecosystem to produce ecosystem services to the local communities and did it reduce climate risks and allow the ecosystem to withstand climate change impacts and stressors?

- Did biodiversity increase after the intervention was put in place?
- Did ecological integrity, ecosystem services and ecosystem functioning improve in ways that benefit the community?
- Are there any trade-offs to other ecosystem services in implementing the intervention?
- Are the ecosystems now functioning in reducing the exposure to climate risks? (Are they reducing storm surges, flood water or drought impacts?)

3. ***Financial and economic effectiveness***

★ Was the EbA intervention cost-effective and economically viable over the long term?

- Was the intervention cost-effective when compared with other interventions?
- Were there any financial or economic benefits over the long term?
- What were the general economic benefits of the EbA intervention?

4. ***Policy and institutional issues***

★ What social, institutional, and political factors influenced the implementation of effective EbA?

- What are the key policy, institutional and capacity barriers or opportunities for implementing EbA at the local, regional and national levels over the long term?
- What opportunities have emerged for replicating, scaling up, or mainstreaming EbA interventions to reduce vulnerability, and how might these influence policy?
- What changes in local, regional or national government or donor policies are required to implement more effective EbA interventions?

climate-related vulnerabilities. This allowed us to capture a broader set of evidence, including traditional practices and natural resource management strategies that align with EbA objectives. Importantly, the review focused on interventions implemented in the past, regardless of whether they were initially designed as long-term climate adaptation responses, if they addressed ecosystem-mediated pathways to human resilience.

2.1. A framework to assess EbA effectiveness

Reid *et al.* [29] developed a framework for assessing the effectiveness of Ecosystem-Based Approaches to adaptation [29,30]. The framework was developed to assess whether EbA interventions can effectively strengthen human adaptive capacity or resilience, and whether EbA can support ecosystem resilience and the provision of ecosystem services. This framework has been tested in several countries, including Kenya, South Africa, Uganda and Chile, focusing on different EbA project site initiatives within terrestrial ecosystems. The framework assesses EbA effectiveness through four main pillars: (1) benefits to human communities, (2) ecological outcomes, (3) financial and economic efficiency, and (4) political and institutional factors influencing EbA implementation. Although the framework provides a strong foundation for assessing EbA interventions, it is limited by its reliance on high-level, lumped concepts (e.g., resilience) which are often difficult to measure, are not one dimensional and without linking to a suggested published methodology. For example, one of the questions for pillar 1 is “Did the EbA initiative improve resilience and adaptive capacity of local communities and help the most vulnerable?” Resilience is a complex and multi-dimensional concept. Resilience as a metric typically incorporates diverse interrelated factors, including social, economic, institutional, and ecological factors, which need to be broken down explicitly. Suggested lumped metrics as an indicator within a long list of other indicators is not straightforward as these concepts are multidimensional and defined, measured and assessed in different ways [31].

In this paper we adopt and modify the Reid et al., [29] framework to assess the effectiveness of EbA interventions in freshwater ecosystems by refocusing it on specific indicators that can capture whether an EbA intervention reduces climate risk. This included incorporating elements of the IPCC AR6 climate risk framework [32,33] aligning with the idea that the actual effectiveness of EbA should contribute to a reduction in the climate risk and impacts through reducing vulnerability to climate change. Vulnerability reduction through EbA interventions is therefore a key strategy for reducing climate risk. In our approach vulnerability is framed according to the IPCC AR6, where vulnerability is a component of climate risk (Supplementary information 1; Appendix A) and is defined as the propensity or predisposition to be adversely affected. It encompasses several elements, moving beyond the previous definition of a system being susceptible to and unable to cope with adverse climate impacts. Vulnerability now encompasses sensitivity to harm, lack of capacity to cope and lack of capacity to adapt and this accounts for social and contextual factors that contribute to vulnerability. Sensitivity or susceptibility to harm refers to the degree to which a system is affected by climate-related hazards, while lack of capacity to cope addresses a system's ability to manage and respond to the immediate impacts of a climate-related event. Lack of capacity to adapt refers to a system's ability to adjust over time to changing climate conditions and reduce its vulnerability to long-term impacts. In this review, both ecological (freshwater) and social (people and communities) vulnerability is considered [34] drawing on categories related to freshwater ecosystem services and sustainable livelihood [35,36].

We further modify Reid *et al.* [29]’s framework by revising the main pillars. We adjusted Pillar 2 and 3 on ecosystem and economic effectiveness to address some limitations in the framework. The Reid *et al.* [29] framework (Appendix B) adopted a broad, largely descriptive approach that focused on identifying ecosystem changes and stressors, but it did not explicitly operationalise stressors and pressures in terms of ecological vulnerability, nor did it clearly link ecosystem change to biodiversity outcomes, ecosystem functioning, or concrete climate risk reduction benefits for communities. In Pillar 2 it mentions the concept of ecological resilience, which is difficult to define and empirically measure in applied, data-limited contexts. The modified framework addresses these gaps by reframing ecosystem effectiveness around reduced ecological vulnerability, explicitly assessing how EbA interventions improve biodiversity, ecological integrity, and ecosystem functioning under multiple interacting stressors, and by directly linking these ecological outcomes to measurable reductions in climate risk exposure (e.g. flooding or drought impacts) it clearly demonstrates how EbA reduces vulnerability to climate risks. In parallel, Pillar 3 was retained as it was, as it already provided a robust assessment of economic effectiveness by explicitly considering long-term economic viability, comparative cost-effectiveness relative to alternative interventions, and the sustainability of financial and economic benefits. Pillar 4, which examines the policy and institutional dimensions of EbA implementation, was likewise applied without modification, as it remained well suited to capturing governance, enabling conditions, and institutional factors influencing EbA implementation. By applying this modified framework to the papers we review, we are thus able to evaluate the effectiveness of EbA interventions by their ability to reduce climate risk via reducing vulnerability across different contexts, whether sectoral, national, or local [37].

2.2. Searches and screening process

This review employed a systematic approach to the literature review to answer focused research questions, following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [38]. The review incorporated a tailored version of the PICO (Population, Intervention, Comparison, Outcome) framework (Table 2) to guide the search strategy, search terms, and search query. Specifically, the “Population” term was restricted to South Africa to ensure a country-specific focus, while the "Intervention" term encompassed all EbA interventions in freshwater ecosystems. The “Outcome” term was defined to capture ecosystem services and socio-economic outcomes resulting from these EbA interventions. The standard PICO framework was then adapted by omitting the “Comparison” component and introducing an "Ecosystem" term to ensure comprehensive inclusion of freshwater ecosystem types. Additionally, an extra “Outcome” term was added to capture papers focused on EbA interventions that made links to climate change adaptation. The “Population” term was expanded to include the human components involved in the EbA interventions, such as communities, villages, and farms, to capture the social dimensions of

Table 2
PICO elements of the research question that guided the search strategy, search terms and the search query.

Population	Intervention
The population of interest. Country specific and only limited to South Africa.	Any EbA strategy that uses biodiversity and ecosystem services to help people adapt to the adverse effects of climate change e.g. wetland rehabilitation, restoration, invasive alien clearing.
Ecosystem	**Outcome**
Habitats or environments where freshwater is present, including bodies of water like lakes, ponds, rivers, streams, and wetlands, characterised by low salt concentrations.	Ecosystem services and socio-economic outcomes resulting from the EbA interventions implemented.
Extra Population term	**Extra Outcome term**
Specific group of individuals involved in the EbA interventions e.g. community, village etc	Outcomes from the EbA intervention related to climate change adaptation, including vulnerability, sensitivity, and resilience

these interventions more comprehensively. This modified PICO framework informed the inclusion and exclusion criteria and shaped the search strings used (Supplementary information; Appendix C). The systematic search targeted peer-reviewed literature in the Web of Science database and was conducted from September to December 2024.

Following the PRISMA guidelines, a total of 117 articles were found through the Web of Science database. These were limited to articles that were written in English and only those with titles relevant to the inclusion and exclusion criteria developed from the research questions (Table 3). After abstract screening, a total of 36 articles were selected for full text retrieval. After full text screening, only 22 articles were found to be relevant. The records which were eligible after applying the research framework were 14 articles and 13 more articles were added through backward citation searching i.e., by screening reference lists of included papers to identify additional papers. A total of 27 articles were used for the data extraction (Supplementary information 1; Appendix D). Abstract and full-text screening were conducted by the lead author. To ensure consistency and accuracy in the screening process, a clear set of predefined inclusion and exclusion criteria was developed prior to screening and applied systematically across all records. To minimise bias and enhance reliability, a pilot screening of a subset of abstracts (n = 20) was conducted to test the criteria and refine the screening protocol. During full-text screening, detailed notes were kept for each decision. Consistency checks were performed by revisiting a random sample of screened articles at both the abstract and full-text stages to confirm alignment with the criteria. This approach ensured a structured and transparent process.

2.3. Coding strategy

Evidence was extracted from 27 selected peer-reviewed articles using a standardised coding framework compiled into a codebook (Supplementary information 2). The codebook was developed to capture key information on the article itself, the type of intervention, the methods used, and the reported outcomes. Each distinct location where an EbA intervention was implemented was treated as a separate case and assigned a unique case ID. Articles describing multiple intervention sites were coded as multiple cases. To ensure objectivity, only information explicitly reported in each article was used during the coding process. Coding of each source was primarily categorical but open-ended responses were used for questions that required more detail or descriptive input.

To determine the geographic distribution of each EbA intervention, both the specific locality and the corresponding South African province were recorded. The biome in which each intervention was located was classified using predefined biome categories established by Rutherford *et al.* [39], including Savanna, Grassland, Fynbos, Nama Karoo, Succulent Karoo, Forests, Albany Thicket, Indian Ocean Coastal Belt, and Desert. Each intervention was also assigned to a freshwater ecosystem type based on standard classifications [40], including river, wetland and dam. Following this system, streams are classified under the broader category of rivers, which are defined as primary units encompassing all linear water bodies with clearly defined beds and banks and concentrated flow, whether permanent or seasonal. This classification further recognises specific stream types, such as mountain headwater streams and mountain streams, as sub-categories of rivers. Where relevant, additional detail on whether the intervention occurred in a catchment or riparian system was noted. We acknowledge the diversity of wetland types and the various ways in which they function to provide distinct ecosystem services. In this review wetlands are defined as land that is transitional between terrestrial and aquatic systems, where the water table is usually at or near the surface, or the land is periodically covered with shallow water, and which land in normal circumstances supports or would support vegetation typically adapted to life in saturated soil [41]. However, for this review, all wetland types were grouped under a single category, wetland, to maintain consistency and simplify classification across EbA interventions. The type of EbA intervention implemented at each site was categorised into four predefined groups: revegetation, invasive alien management, constructed/artificial wetlands and structural interventions. Additional intervention types were included if they emerged from the literature. Intervention duration was recorded as an open field in years. In this review, the duration of the intervention is defined as the entire period from the initial year the intervention was implemented to the point at which data were collected following its implementation. The methodological approach of each source was coded as empirical (based on observations), conceptual, or modelling. The data type was classified as either qualitative or quantitative. The availability of data related to each intervention was recorded in an open field, including whether pre- and post-intervention data were provided.

To assess the effectiveness of each EbA intervention, socioeconomic benefits to people (Pillar 1) were coded using twelve predefined categories. Ten of these were adapted from Rasmussen *et al.* [35]: health, education, food security (availability), social relations or values (e.g., cultural benefits), employment and income, other income, justice (fairness and equity), property rights (land tenure security), natural capital (access to a resource) and material assets (e.g., infrastructure, tools). Two additional categories, water security and energy security, were included to capture other socio-economic outcomes of EbA interventions. Water security reflects not just increased water availability but also improved access and reliability for domestic and agricultural use, which are essential for livelihoods and resilience. Energy security was added to account for benefits such as improved access to sustainable fuel sources or energy services, which support household needs and productive activities. We only recorded socioeconomic benefits that were quantitatively reported in each source. For example, if an EbA intervention led to improved streamflow, this was recorded as a natural

Table 3
Search Terms and Criteria for Inclusion and Exclusion of Literature to Address the Research Question.

Documents used for the systematic review were used to answer the following questions:

Primary Question:

How effective is EbA in freshwater ecosystems in South Africa at helping people adapt to the adverse effects of climate change while contributing to socio-ecological benefits?

Secondary Key Questions:

What are the specific impacts of EbA interventions on freshwater biodiversity, ecosystem functioning, and the provision of ecosystem services?

What socio-economic benefits do local communities derive from the implementation of EbA strategies in freshwater systems?

How do EbA interventions in freshwater ecosystems reduce vulnerability for both ecosystems and communities in the face of climate change?

What governance frameworks and policy mechanisms support or hinder the effective implementation of EbA in freshwater ecosystems for climate resilience?

Exclusion criteriaWe excluded studies:

- That were from estuaries, salt pans and marine ecosystems
- That did not assess ecosystem services, socio-ecological benefits or adaptation outcomes related to people.
- That lacked measurable outcomes of EbA effectiveness.
- That were not country-specific to South Africa.
- That were broadly interdisciplinary without a direct focus on EbA interventions.
- That were opinion cases, conceptual papers or policy briefs without empirical data or case study analysis.

capital benefit. If the source further indicated that the increased streamflow enhanced community access to water for domestic use or agriculture, it was also recorded as a water security benefit. However, in cases where streamflow improvements were mentioned without any evidence of human use, the benefit was categorised solely under natural capital. Employment and income were combined into a single benefit category when income was derived directly from employment related to the EbA intervention (e.g., jobs created during alien plant clearing). In contrast, income from non-employment sources, such as selling firewood resulting from the intervention, was classified separately under "other income."

For each benefit, a description was recorded to document how the benefit was reported in the source. Where specific beneficiary groups were identified (e.g., women, youth), this was also noted. The level of community involvement in each intervention was categorised as none, low, medium, or high. If not mentioned in the source, this was coded as "not specified."

Ecological outcomes (Pillar 2) were recorded by coding for the ecosystem services provided by the intervention. These were based on the WRC Wet-EcoServices Version 2 [36], which, although developed for wetlands, was extended to other freshwater systems (e.g., rivers, dams) based on expert input. The predefined categories included: flood attenuation, streamflow regulation, sediment trapping, phosphate assimilation, nitrate assimilation, toxicant assimilation, erosion control, carbon storage, biodiversity maintenance, provision of water for human use, provision of harvestable resources, food for livestock, provision of cultivated foods, cultural and spiritual experience, tourism and recreation, and education and research (Supplementary information 2). Descriptions of each ecosystem service were recorded where the source provided relevant details. Any negative ecological and socioeconomic outcomes were recorded in an open field with no predefined categories. To assess the direction of change in ecosystem service delivery, each intervention was coded as having resulted in an increase, decrease, both, or no change.

To understand the relevance of each intervention to climate change adaptation, we evaluated the extent to which the sources explicitly or implicitly established a link between the EbA intervention and climate adaptation outcomes. Each source was categorised as either “None” (no mention of a climate adaptation link), “Inferred” (a link could be interpreted but was not explicitly stated), or “Supported by data” (a clear, evidence-based link demonstrated through empirical findings). For those sources that did have a climate adaptation link, whether inferred or supported by data, the specific climate hazards addressed by the intervention were coded using predefined categories from IPCC AR6 [42] (see Supplementary information 2 for full list). If reported, any information on any aspect of the economics of each intervention was coded. This included any reference to implementation costs, comparisons with other adaptation strategies, or the use of existing local resources. Policy-related implementation challenges and research gaps were recorded in open fields, depending on the information available in each source. Finally, the quality of evidence was assessed based on criteria reflecting the reliability and robustness of the findings and coded as low, medium, or high.

3. Results

In total 46 cases were used in this review from the 27 reviewed articles which met our selection criteria. Of these 27 studies only 11% (3 studies) explicitly referred to EbA. However, the remaining studies were included as EbA-relevant sources based on the inclusion criteria, as they provided evidence on interventions aimed at managing and adapting ecosystems in response to climate change. Although these studies did not use the term "EbA," they employed related terminology, often within broader categories including invasive alien management and revegetation. Therefore, the results presented in this review are based on an analysis of both explicit and implicit EbA-related sources, recognising their relevance to the assessment of EbA effectiveness. The sources used in this review were published across different journals from 1999-2024.

3.1. Sources and quality of evidence

Across all freshwater ecosystem types, 89% of the cases employed empirical methods to assess the effectiveness of EbA, while 11% relied on modelling approaches, and none of the sources used conceptual methods. Regarding data types, 59% of the cases generated qualitative data, 9% produced quantitative data, and 33% incorporated both qualitative and quantitative data. When examining the types of outcomes reported, 7% of the peer-reviewed cases assessed the economics of EbA interventions but did not report any ecological or socio-economic outcomes. A majority (74%) focused solely on ecological outcomes, with no socio-economic analysis. Conversely, 11% of the studies reported only socio-economic outcomes, while just 9% captured both ecological and socio-economic outcomes.

3.2. Distribution of evidence

Evidence on the effectiveness of EbA interventions was recorded across all provinces in South Africa. The Western Cape accounted for the highest proportion of cases (39%), followed by the Eastern Cape and KwaZulu-Natal (each 13%), Mpumalanga (11%), and the Northern Cape (7%). Fewer cases were documented in Limpopo (5%) and the North West Province and Free State (both 4%), with the Gauteng Province having the least representation (2%), and cases at the national level representing 2% (Fig. 1c). In terms of ecological context, most EbA interventions were implemented in the Fynbos biome (42%) and the Grassland biome (33%). Fewer interventions were recorded in the Savanna biome (13%), the Succulent Karoo biome (7%) and the Albany Thicket (5%) (Fig. 1b). For the freshwater ecosystem types, most studies focused on rivers (59%) and wetlands (39%), with considerably fewer studies conducted in dams (2%) (Fig. 1a).

3.3. EbA interventions

The four main types of EbA interventions identified across the reviewed sources were invasive alien management, artificial wetlands (constructed wetlands), revegetation and structural interventions (Table 4). The most frequently documented intervention was invasive alien management, accounting for 87% across all ecosystems. It was most applied in river ecosystems (45.6%), followed by wetlands (8.8%) and dams (1.8%). Structural interventions, which made up 39%, were mostly implemented in wetlands (28.1%) and a smaller proportion in rivers (5.3%). Revegetation interventions made up 7.0% of the total, occurring in rivers (5.3%) and wetlands (1.8%) (Fig. 2). Artificial wetlands were the least common intervention type, contributing to 4% of all records and occurring exclusively in river ecosystems. Overall, river ecosystems received the highest proportion of interventions (59.6%), followed by wetlands (38.6%) and dams (1.8%). Most interventions were implemented in combination rather than in isolation. For instance, invasive alien species removal was sometimes paired with revegetation. In other cases, multiple interventions were employed at single sites to achieve comprehensive restoration. At the Killarney Wetland, for example, EbA interventions involved a combination of structural interventions, including concrete clads, plugs, weirs, earthen berms, and a spreader canal.

The duration of the EbA interventions in the sources reviewed ranged from 1 to 12 years, with a mean of approximately 5.3 years. 17% of the interventions were implemented in 1 year. Most interventions (61%) were implemented between 2 and 7 years, indicating a trend toward relatively short to medium-term EbA interventions. Despite this, 15% of the interventions were implemented for longer, up to 8-12 years.

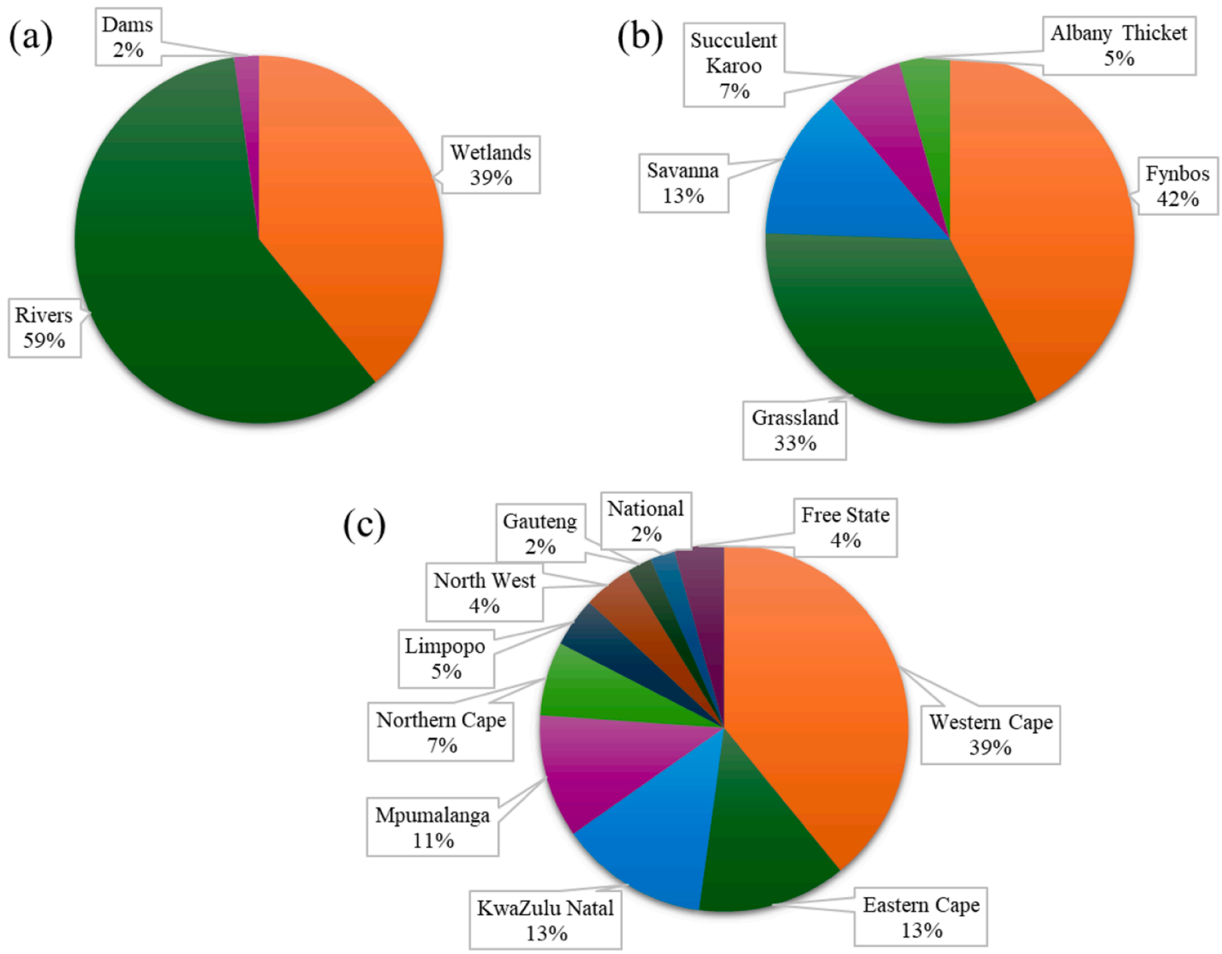

Fig. 1. Distribution of EbA evidence (n = 46 cases) across South Africa by (a) ecosystem type, (b) biome, and (c) province. The pie charts illustrate the proportion of documented cases within each category.

3.4. Socio-economic outcomes from EbA

From the 15 cases reviewed, which reported on socio-economic benefits (Pillar 1). The most frequently cited benefit across the interventions was employment and income, making up 86.7%. Education was the second most common benefit, accounting for 66.7% of the total, with many projects incorporating skills development, awareness-raising, or capacity-building components. Natural capital was also frequently reported, occurring in 8 cases (53.3%).

Other notable benefits included social relations or values (13.3%), material assets (13.3%), and justice (6.7%). Water security and energy security were each 13.3% (Fig. 3). Other income was reported once (6.7%), reflecting additional economic opportunities not directly linked to employment. For this case, the sites were close to the road, and there was an opportunity for the felled larger wood from invasive alien clearing to be sold as firewood.

In this review, community involvement was not specified in 31 out of 46 cases (67.4%). Of the 15 cases where involvement was reported, 8 cases (17.4%) showed medium involvement and 7 cases (15.2%) demonstrated high involvement. No cases reported low or minimal participation. These results suggest that, where community engagement is documented, participation tends to be moderate to high.

From the reviewed literature many projects are implemented in areas prioritised for ecological restoration rather than where the poorest or most vulnerable populations reside, limiting their broader adaptive impact. Furthermore, weaknesses in labour recruitment processes, poorly executed exit strategies, and irregular work distribution were noted, resulting in poverty reduction outcomes that are often limited and short-lived In one reported case, recruitment of labourers was undermined by local corruption, where a community leader auctioned a contractor position to the highest bidder [56].

3.5. Effectiveness for the ecosystem

Analysis of EbA across South African freshwater ecosystems revealed distinct patterns in ecosystem service delivery post-EbA intervention (Fig. 4). In river ecosystems, 28 cases (61%) recorded an improvement in the following ecosystem services post-EbA: streamflow regulation (56%), biodiversity maintenance (59%; e.g., native fish/plant recovery), water provision for human use (19%) and provision of harvestable resources (11%). While food for livestock and tourism, and recreation were recorded in 4% of the studies. Wetlands (18 cases, 37%) through structural interventions and invasive species removal significantly recorded improved erosion control (78%), carbon storage (78%) flood attenuation (67%), biodiversity maintenance (61%), nitrate removal (56%), toxicant removal (56%), phosphate trapping (44%), streamflow regulation (17%). 94% of EbA in wetlands of the papers reviewed provided ≥3 ecosystem services simultaneously. The only case for dams led to improved biodiversity maintenance through the biological control of water hyacinth. Water-related ecosystem services (streamflow regulation, provision of water for human use, flood attenuation) were recorded in 78% of all cases. There was more evidence available on wetlands improving a greater diversity of ecosystem services than for rivers.

Out of 46 cases evaluating the effects of EbA interventions on ecosystem services, 40 cases (approximately 87%) showed a clear increase in ecosystem service provision. Meanwhile, 6 cases (about 13%)

Table 4
Examples of EbA interventions from the literature in the systematic review.

EbA Intervention	Definition and examples from sources
Structural interventions	Structural interventions refer to mechanical or engineered structures specifically designed to mitigate environmental degradation, particularly by addressing issues related to erosion and uncontrolled water flow. These hard interventions provide immediate stabilisation by reducing water velocity and preventing further landscape damage, contrasting with bio-engineering approaches that rely on vegetation to achieve more gradual, long-term ecological balance [43]. Examples of structural interventions include concrete and gabion structures [44]; concrete clad, plugs, weir, earthen berm, spreader canal [45,46]
Invasive alien management	Management practices aimed at the targeted removal of non-native species that threaten the ecological balance and health of ecosystems [47]. Examples from this review include the targeted eradication of smallmouth bass (*Micropterus dolomieu*) from Rondegat River using the piscicide rotenone [48], the mechanical removal of rainbow trout (*Oncorhynchus mykiss*) from Krom River [49], the mechanical removal of alien trees such as *Eucalyptus, Pinus& Acacia* along the riparian areas along a river [50–52]
Constructed/Artificial wetlands	Human-made engineered systems that simulate natural wetland processes, such as water purification and habitat creation, and are constructed for purposes like wastewater treatment, stormwater management, or biodiversity enhancement [53]. Examples include artificial wetlands [54].
Revegetation	The manual planting of vegetation to restore natural habitats. This includes planting native grasses, sedges, and other flora that are adapted to the natural conditions, which helps to improve ecosystem functions. Examples include the introduction of propagules of native plant species with some sown as seeds and some as cuttings [55].

exhibited both an increase and a decrease in the direction of change.

3.6. Economics of EbA

In total 21 out of 46 of the cases (46%) explicitly mentioned either the cost of implementation of the EbA intervention or the cost against other alternatives. The remaining 25 (54%) did not provide this information. This indicates that although nearly half of the studies considered the economics of EbA through some dimension, there is still a notable gap in consistent reporting for this.

Among the studies that did look at the economics, evaluations ranged from detailed cost analyses to more qualitative judgments. For example, Black *et al.* [24] reported that EbA restoration in the Kamiesberg wetlands was more cost-effective than conventional engineered alternatives, highlighting the financial viability of ecosystem-based adaptation. Similarly, Shelton *et al.* [49] provided a concrete expenditure breakdown for a mechanical fish removal project, costing R150,000 over 40 days. Several case studies (e.g., [50,51]) emphasised the economic advantage of early intervention, particularly for managing invasive species.

Box 1 presents a case study from the review that applied a standardised method to assess the cost-effectiveness of EbA interventions. This case study is included because it provides a robust, empirical example of how cost-effectiveness of EbA interventions can be assessed using clearly defined costs and cost–benefit ratios. By explicitly justifying the costs of interventions relative to the improvement in ecological conditions, it aligns closely with Pillar 3 and offers a practical basis for evaluating economic effectiveness and comparability across EbA options. Overall, findings from this review highlight that there is still a lack of widely adopted, consistent methodologies for evaluating the cost-effectiveness of EbA across different contexts.

3.7. Addressing climate hazards through EbA

For the EbA interventions in this review, only 19.6% had a clear link to climate adaptation, which was supported by data. While in the majority of cases (52.2%), the climate adaptation link was inferred. So out of the 46 cases reviewed, 71.7% (33 out of 46 cases) had a climate adaptation link. Amongst these, a total of six climate hazards addressed by the EbA interventions were identified. The most frequently addressed hazards were river floods and heavy precipitation/pluvial floods, appearing in 20 of 33 cases (60.6%). Hydrological drought was also prominent, cited in 16 cases (48.5%), followed by agricultural and

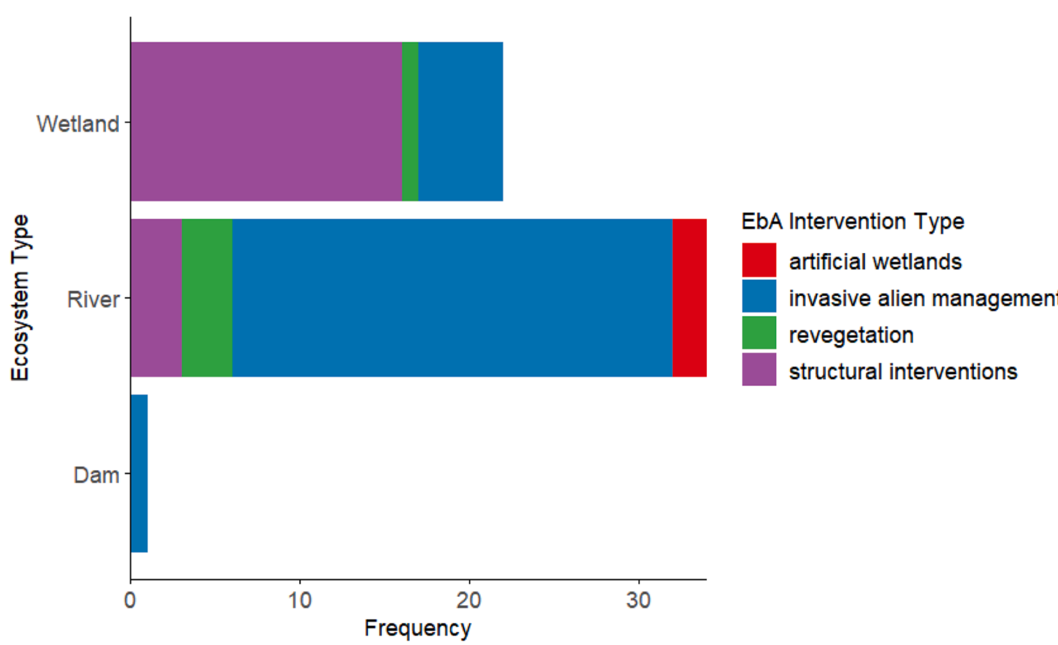

Fig. 2. Frequency of EbA intervention types across different freshwater ecosystem types. Stacked horizontal bars represent the frequency of broad EbA intervention types implemented within each ecosystem type.

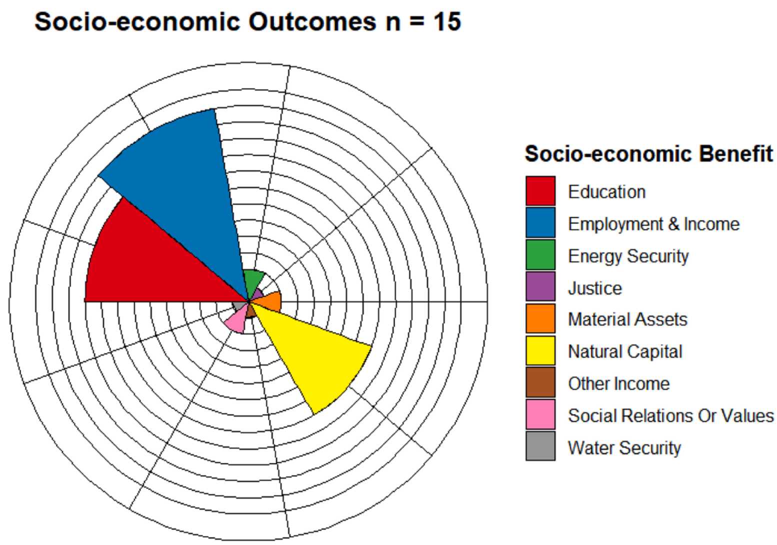

Fig. 3. Flower diagram of socio-economic benefits for EbA interventions in South African freshwater ecosystems (n = 15). Each petal represents one benefit category, with radial length proportional to the number of cases reporting that benefit. Distinct colours (as shown in the legend) differentiate benefit types.

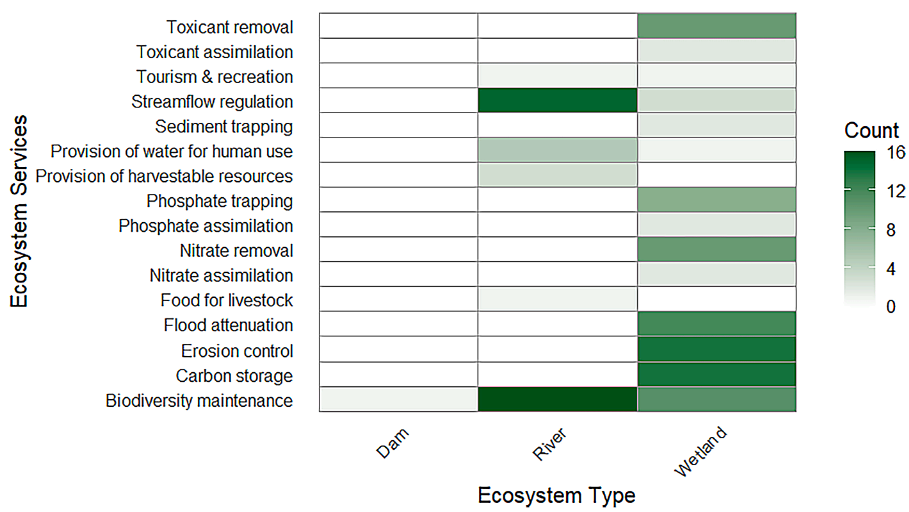

Fig. 4. Heatmap illustrating the frequency of ecosystem services provided by EbA interventions across different freshwater ecosystem types. Darker shades indicate higher frequencies, highlighting the extent to which specific ecosystem services are associated with particular ecosystem types.

ecological drought in 8 cases (24.2%), and aridity in 7 cases (21.2%). Fire weather was the least represented climate hazard, identified in 4 cases (12.1%). However, in 28.3% of the cases, there was no link between EbA and climate adaptation.

3.8. Policy and institutional issues

A key policy issue emerging from the reviewed literature in implementing EbA is the lack of effective integration between EbA interventions and broader societal goals. Communities that do not see direct benefits from implementation may deprioritize environmental concerns when faced with pressing personal or communal needs, such as poverty alleviation or access to basic services. This highlights the failure to address trade-offs between environmental protection and other development priorities, undermining the broader integration of environmental policies across social, economic, and cultural domains [44]. Most EbA projects must navigate the complex interplay between formal governance structures (national, regional, and local government) and traditional governance structures (chiefs, headmen, and traditional councils). In the Tsitsa Project empowered actors in the form of Community Liaison Officers were provided with employment and they acted as key agents of participatory governance development. They participated in workshops and were mentored into running workshops in the expansion phase of the project which helped embed understanding of restoration among people in the catchment [58]. The evidence reveals a strong dependence on public funding (DFFE) for EbA interventions. This highlights a need for more diverse and stable funding mechanisms, particularly considering the limited public resources and the need to attract private sector investment [54,59]. The sources also highlight that EbA interventions such as invasive alien clearing should be fully integrated into broader adaptation strategies and water security plans [60]. In the case of EbA interventions that were under government projects such as the Working for Water (WfW) program, the program's effectiveness is hinged on balancing its multiple objectives and ensuring that the benefits reach the intended beneficiaries. The Government of South Africa commonly sets multiple goals for workfare interventions for economic, environmental and social objectives. Evidence showed that the program's recruitment process is primarily determined by the distribution of alien invasive plants, which may not align with the areas of greatest poverty [56].

Box 1
Case Study: Assessing the economic viability of wetland restoration in South Africa

This case study draws on data from South Africa's Working for Wetlands (WfWetlands) programme to evaluate the cost-effectiveness and economic viability of Ecosystem-based Adaptation (EbA) interventions. The study assessed ecological outcomes and costs at 13 sites, using a rapid assessment approach suitable for resource-limited, government-funded projects.

Cost-effectiveness was measured following the guidelines of Cowden and Kotze [57], with inflation-adjusted implementation costs obtained from WfWetlands records. The primary metric was the cost per hectare equivalent of ecological condition gained or secured, where hectare equivalents were calculated by multiplying the spatial extent of a wetland (in hectares) by its ecological condition score (using WET-Health). The contribution of restoration was derived from the difference between "without" and "with restoration" hectare equivalents.

An appraisal was then made on whether these costs were well justified, moderately justified, or not justified, based on the restoration's contribution to ecosystem services, using WET-EcoServices indicators. Costs were generally deemed "not justified" if they exceeded R500,000 per hectare equivalent and did not lead to substantial improvements in ecosystem services.

The results showed that 7 of the 13 sites had costs that were well justified, including Boekenhout-fontein, Colbyn wetland, Draaikraal wetland, Eselfontein seep, Hlatikulu (Nsonge portion), Lake Fundudzi wetland, and Ratelrivier wetland. These sites demonstrated favourable cost-benefit ratios, with restoration contributing meaningfully to both ecological condition and ecosystem services.

In contrast, two sites, Eselfontein wetland and Hogsback seep, had costs that were not justified. The Eselfontein site had a cost per hectare equivalent of R633,026, with only slight ecosystem service improvements and potential recovery constraints due to invasive species. Hogsback had an even higher cost per hectare equivalent of R1,040,755, with minimal gains across all assessed ecosystem services.

The study highlights that costs varied amongst different sites and that interventions requiring hard structural solutions were significantly more expensive than those addressing invasive species. It concludes that cost-effectiveness assessments must account for site-specific ecological contexts, the type of restoration problem, and the expected contribution to ecosystem service provision, reinforcing the importance of strategic, context-aware EbA planning.

4. Discussion

We found 46 cases of EbA interventions in South African freshwater ecosystems reducing social or ecological vulnerability to climate risk via benefits to people and ecosystems. This includes all cases with either a socioeconomic or ecological outcome. This is far more than has been documented in other global reviews which have a few cases from Southern Africa [26], especially given the narrow focus of this review. A large proportion of the evidence synthesised in this review was derived from empirical studies (86%), representing a markedly higher share than reported by Rebelo *et al.* [25], where only 4% of the evidence was empirical and 91% was conceptual. This divergence likely reflects differences in review scope and inclusion criteria. In particular, the present review was restricted to peer-reviewed literature, which may bias the evidence base towards empirically grounded studies, whereas Rebelo *et al.* [25] included both peer-reviewed and grey literature. This evidence of EbA suggests that there is some improvement in coherent understanding to the extent to which EbA can contribute to effective adaptation [8]. However, this review reveals several critical gaps in the current evidence base for EbA in South Africa. First, there is a clear geographical imbalance, with most documented studies concentrated in the Western Cape, highlighting the need for broader spatial representation across South Africa's diverse freshwater systems. There is also a notable lack of systematic evaluation of both ecological and socio-ecological outcomes of EbA projects. This ideally requires an initial socio-economic and environmental baseline survey before initiating the EbA intervention as well as post-intervention monitoring extended for a sufficiently long period to pick up positive results, and mirrors a global challenge, particularly within government-funded programmes in developing countries, where resources and capacity for rigorous monitoring and evaluation remain limited [51].We therefore need to build locally tailored information that has robust baselines that help us understand the current biophysical context where EbA interventions are implemented. This is therefore increasingly important for adaptation interventions such as EbA, to be able to demonstrate their effectiveness [61].

Although many interventions demonstrate benefits directly linked to reducing the vulnerability of people and ecosystems, there is limited evidence on how and to what extent these benefits translate into climate change adaptation. For example, only 7 cases provided an explicit, data-supported link between observed benefits and specific climate hazards. The evidence-base was particularly strong for wetland ecosystems followed by rivers. There was very little evidence available for EbA in artificial systems such as dams. This evidence gap suggests that more focused research is needed to better extract literature in large water systems such as dams. The inconsistent use of EbA terminology also continues to obscure the evidence landscape, making it difficult to assess effectiveness, compare outcomes, and identify best practices [62,63].

4.1. Ecological outcomes

Of the reviewed literature 59% of the total cases reported on ecological outcomes from EbA interventions. Assessing the degree to which EbA interventions achieved their intended goals is essential for understanding their overall effectiveness [46]. The targeted objectives of EbA from the literature, such as restoring streamflow, improving water quality, enhancing water yields, restoring ecosystem health, removing invasive alien species, and promoting biodiversity recovery, were largely realised through ecosystem restoration processes. These processes re-established regulating ecosystem services, including flood attenuation, erosion control, and nutrient assimilation, demonstrating the capacity of well-designed EbA interventions to deliver multiple ecological benefits simultaneously. Improvements in ecosystem services recorded across the cases reviewed are understood as a proxy for a partial return towards healthier ecosystem functioning, rather than conclusive evidence of comprehensive ecological recovery. Improvements in these ecosystem services in the review can be viewed as contributing to reducing climate vulnerability by buffering exposure to climate hazards, lowering the sensitivity of livelihoods to environmental change. The recurrence of ecosystem services like streamflow regulation and biodiversity maintenance across EbA interventions thus indicates that many projects successfully addressed ecological objectives and hence reduced climate vulnerability. For instance, wetland rehabilitation projects that aimed to restore natural hydrological regimes also enhanced carbon storage, phosphate trapping, nitrate removal and toxicant removal [46]. Similarly, invasive alien plant clearing initiatives along rivers contributed to improved streamflow and biodiversity maintenance [64,56,65]. However, the degree of success varied, often constrained by limited long-term monitoring and the absence of standardised indicators to quantify the extent of ecosystem service recovery. Overall, the evidence suggests that while EbA interventions are effective in delivering multiple co-benefits, their success is context dependent. It is therefore important, when implementing EbA, to reflect on outcomes through continued learning, ensuring that future investments are directed toward interventions with demonstrated effectiveness and success.

Eighty seven percent (87%) of the cases reviewed showed a clear positive direction of change in ecosystem services across different freshwater ecosystem types. This finding suggests that EbA interventions can lead to favourable ecological outcomes, primarily by reducing ecosystem vulnerability and enhancing the capacity of ecosystems to provide services. Despite this strong positive trend, 13% of the reviewed cases exhibited both increases and decreases in the direction of change for ecosystem services, indicating that EbA outcomes can be context-dependent and influenced by site-specific ecological and management factors. Several cases from this review reported unintended negative impacts of EbA interventions. In some cases, biological control measures showed initial success but failed to maintain long-term effectiveness [50]. Vegetation degradation in river catchments after invasive alien clearing was observed over time, with a significant decline in herbaceous and grass cover and an increase in bare soil and litter, resulting in reduced surface stability and a heightened risk of downstream sedimentation due to soil erosion. Interventions, such as the removal of *Eucalyptus grandis* in the Sabie River catchment, led to the emergence of other alien species, creating a new invasive assemblage. The impacts of this 'new' alien assemblage on ecosystem services are less clear than with *E.grandis* [64]. Mechanical and fire-based control methods (e.g., Fell-only, Fell & Burn) for invasive alien control in river catchments were associated with poor native plant recovery, reduced biodiversity, and increased fire risks due to unremoved debris [66]. Furthermore, burning promoted the germination of alien species and was found to be ecologically damaging in some instances. Secondary invasions by alien and weedy native grasses were reported, along with reinvasions by species such as *Acacia* [67]. Negative outcomes were also observed across both ecological and socio-economic dimensions, highlighting the complex trade-offs that can emerge from EbA interventions. For instance, following a wetland rehabilitation project, vegetation recovery did not occur as anticipated. Previously, farm workers harvested *Juncus punctorius*, a species that thrives in very wet conditions and is traditionally used for weaving. After wetland rehabilitation, however, this species was replaced by *Juncus effusus,* which is unsuitable for weaving. This shift represents a case where a positive ecological benefit, the restoration of wetland hydrology, led to a socio-economic drawback by reducing access to a culturally and economically valuable resource.

4.2. Socio-economic outcomes

Only 33% of the reviewed literature reported socio-economic outcomes from EbA interventions, clearly revealing a significant evidence gap in this area. Employment and income was the most frequently documented benefit, particularly in projects involving invasive alien plant clearing and wetland rehabilitation. However, questions remain about the extent to which these interventions effectively reduce the vulnerability of local communities to climate change. Overall, while EbA interventions can generate diverse socio-economic benefits that support livelihoods and community well-being, these gains are typically temporary, as most employment opportunities are contract-based and end once project implementation concludes [54].

Evidence of community involvement in EbA projects was generally limited across the reviewed sources. Yet, community participation is a critical component of effective EbA implementation, as higher levels of local engagement are often associated with improved social and ecological outcomes [63]. Despite recognition of its importance in some interventions, detailed reporting on the nature and extent of community involvement remains scarce. This lack of documentation makes it difficult to assess how participation influences EbA project success and long-term sustainability. Ensuring that communities are placed at the centre of EbA planning and implementation is therefore essential for enhancing both local ownership and the overall effectiveness of adaptation outcomes.

While several studies reported positive socio-economic outcomes, there were also clear examples of trade-offs that may limit the extent to which these interventions reduce vulnerability in the longer term. For instance, in programmes such as *Working for Wetlands*, employment was intended to follow Expanded Public Works Programme (EPWP) guidelines prioritising vulnerable groups; however, it was not always clear whether these criteria were consistently implemented in practice [44]. Although participants often gained valuable skills during project implementation, these did not necessarily translate into sustained livelihood opportunities, as workers reported limited ability to use these skills to secure further employment. In addition, most employment opportunities associated with EbA interventions were short-term and project-based rather than permanent, meaning that income and livelihood benefits were not sustained beyond the duration of the intervention [56].

4.3. Climate change impacts

From the evidence in this review, only 19.6% had a clear link to adaptation, but in 52.2% the climate adaptation link had to be inferred. EbA interventions are meant to address long-term climate change to reduce the vulnerability of people to such change [8], but without clear links between the EbA interventions done to the climate hazards this may be difficult. A total of six climate hazards were identified as being addressed through the reviewed EbA interventions. The most frequently targeted hazards were river floods and heavy precipitation or pluvial floods, which featured in 60.6% of the cases. In the Upper Berg and Du Toit headwater catchments, for example, restoration initiatives improved water security during dry seasons and drought conditions by enhancing baseflows and water storage in water-scarce regions. Modelled outcomes further indicated that restoration has the greatest positive influence on mid- to low-flow conditions, particularly during dry years compared to wet years [59]. Hydrological drought was the next most frequently addressed hazard, followed by agricultural and ecological drought, and aridity. Collectively, these findings highlight that EbA interventions implemented in South Africa predominantly focus on managing water-related climate hazards.

4.4. Limitations

This review synthesises evidence on the effectiveness of EbA interventions in freshwater ecosystems in South Africa. Although few studies explicitly use the term "ecosystem-based adaptation," many related sources were included due to the diverse terminology used to describe similar interventions. This variation in language across the different sources may have resulted in the omission of some relevant peer-reviewed studies. The review focused exclusively on peer-reviewed literature, as incorporating grey literature proved challenging due to the different databases available, which contain reports on various EbA projects implemented across the country (e.g., SANBI, IIED). This limitation hindered the consistent application of search terms across sources. In our search strategy for EbA, even though we did not exclude them explicitly, search terms used in this review may have not adequately represented this in comparison to the other terms. Where measures of effectiveness were reported across the reviewed sources, the data showed considerable variation because different methods were used to evaluate effectiveness. In many cases, the methods applied were not explicitly designed to assess how interventions reduce vulnerability to climate change. This lack of standardised metrics and targeted evaluation frameworks makes it challenging to determine and compare magnitudes of change and therefore the actual effectiveness of these EbA interventions or to draw meaningful comparisons with alternative climate adaptation strategies. There is, therefore, a strong need to better articulate the adaptation outcomes that EbA projects seek to achieve, to use a common set of specific indicators to track these outcomes, and to fund the monitoring of long-term EbA projects [68].

This review also relies on reported changes in ecosystem services as indicators of ecosystem-based adaptation outcomes, which introduces some limitations. In many cases, these ecosystem improvements (e.g. enhanced streamflow, soil stability, or vegetation cover) are interpreted as contributing to reduced climate vulnerability, but the included studies rarely establish direct, empirical links to vulnerability reduction or climate risk outcomes at the community level. As a result, using ecosystem service changes as proxies for adaptation effectiveness, may overestimate or simplify the relationship between ecological improvements and actual socio-economic resilience. Furthermore, the extent to which these benefits translate into reduced vulnerability is context-dependent, influenced by other factors such as access, governance, and socio-economic conditions, which are not consistently captured across studies. Therefore, while ecosystem service improvements provide valuable insights into potential adaptation pathways, caution is needed in interpreting these as definitive evidence of reduced climate vulnerability.

5. Conclusions

Ecosystem-based Adaptation (EbA) is increasingly recognised as a critical approach to climate change adaptation, highlighting the role of healthy and functioning ecosystems in reducing climate vulnerability and enhancing resilience. The findings of this review indicate that EbA interventions in South Africa's freshwater ecosystems have demonstrable potential to reduce vulnerability to climate change while delivering multiple co-benefits, including improvements in ecological condition and positive socioeconomic outcomes for local communities. However, the evidence base is uneven and limited. Only a subset of studies directly demonstrates adaptation outcomes, and socioeconomic benefits are not consistently reported in the sources. There is strong empirical support for wetland-focused interventions but limited evidence for rivers and dams, underscoring important gaps in current research and implementation. The review further reveals persistent challenges in evaluating EbA effectiveness, particularly the absence of standardised post-implementation assessment methods and indicators. This limits the ability to consistently measure EbA success, compare outcomes across interventions, and translate scientific evidence into policy-relevant guidance. These challenges are compounded by a paucity of evidence on the economic effectiveness of EbA relative to alternative climate adaptation options, which constrains its uptake in decision-making processes. This limited reporting on the economic viability of EbA creates uncertainty regarding sustainable financing mechanisms. While EbA offers multiple long-term benefits, these can only be fully realised if interventions are embedded within well-structured, adequately resourced, and context-specific programmes that integrate ecological, social, and economic dimensions of resilience. Addressing these gaps requires policy frameworks that explicitly recognise and support EbA as a core component of climate change adaptation in South Africa, alongside the establishment of long-term monitoring and evaluation frameworks. Such frameworks are essential, given that many ecological and socio-economic benefits of EbA interventions accrue over extended timeframes and are critical for strengthening the evidence base needed to inform policy, investment, and practice.

CRediT authorship contribution statement

Chipo P. Mungenge: Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Methodology, Formal analysis, Data curation, Conceptualization. **Petra Holden:** Writing – review & editing, Validation, Supervision, Resources, Methodology, Funding acquisition, Conceptualization. **Nancy Job:** Writing – review & editing, Validation, Supervision, Resources, Methodology, Funding acquisition, Conceptualization. **Graham von Maltitz:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.nbsj.2026.100366.

Data availability

The data that supports the findings of this study is available upon request to the authors.

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