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Bibliometric reviews of scientific trends, collaboration networks, and emerging directions in Wetland and Waterways mitigation research

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Systematic Review

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Bibliometric reviews of scientific trends, collaboration networks, and emerging directions in Wetland and Waterways mitigation research

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Abstract

Wetland and waterways mitigation plays a critical role in compensating for unavoidable ecological impacts associated with infrastructure development and land-use change. Although research in this field has expanded considerably over the past three decades, its thematic evolution, intellectual structure, and collaborative landscape have not been comprehensively synthesized. This study presents a bibliometric review of wetland and waterway mitigation research published between 1996 and 2026. A total of 437 publications, retrieved from Web of Science core collection and Scopus following a PRISMA-guided screening process, were analyzed using SciMAT and VOSviewer. SciMAT was applied to examine thematic evolution across four periods (1996-2002, 2003-2010, 2011-2018, and 2019-2026), while VOSviewer was used to analyze author collaboration, country collaboration, and author citation networks. The results reveal sustained growth in scientific output and a thematic shift from foundational wetland mitigation and ecological compensation toward restoration effectiveness, environmental impact assessment, and ecosystem-based management. The United States emerged as the leading contributor to international collaboration, supported by relatively small group of influential authors. The review also identifies key research gaps, including long-term restoration evaluation, standardized assessment frameworks, geographical disparities in research, and the integration of advanced geospatial and decision-support technologies. These findings provide valuable insights into future research, environmental policy, and the sustainable management of aquatic ecosystems.

Keywords

Bibliometric analysis; Compensatory mitigation; Mitigation banking; Wetland restoration; SciMAT; VOSviewer

Highlights

- Maps 30 years of wetland and waterways mitigation research (1996-2026)
- Reveals thematic evolution using SciMAT science mapping techniques
- Identifies global collaboration and influential author citation networks

- Highlights emerging trends in restoration and impact assessment research
- Identifies future priorities for sustainable aquatic ecosystem management

1. Introduction

Wetlands and waterways are among the most productive ecosystems on Earth, providing essential ecological, hydrological, and socio-economic services that support environmental sustainability and human well-being. They regulate floodwater, improve water quality through nutrient retention and sediment filtration, recharge groundwater, sequester carbon, stabilize shorelines, and provide critical habitats for diverse terrestrial and aquatic species (Anaba et al., 2026; Bedford, 1996; Brinson & Rheinhardt, 1996; Hauer & Smith, 1998; Rheinhardt et al., 1997). Beyond their ecological significance, these ecosystems contribute substantially to climate regulation, biodiversity conservation, and the resilience of both natural and built environments. As global urbanization, infrastructure expansion, agricultural intensification, and industrial development continue to accelerate, wetlands and waterways are increasingly subjected to fragmentation, degradation, and permanent conversion, resulting in substantial losses of ecosystem functions and services (Brown & Lant, 1999; Kaden et al., 2026; Moreno-Mateos et al., 2012; M. M. Robertson, 2004).

To address these losses, compensatory mitigation has become a central component of environmental policy in many countries. Within the United States, Section 404 of the Clean Water Act established a regulatory framework requiring unavoidable impacts to wetlands to be compensated through restoration, creation, enhancement, or preservation of aquatic ecosystems. This policy objective, commonly referred to as the "no net loss" principle, has significantly influenced environmental management over the past three decades (Allen & Feddema, 1996; Bedford, 1996; Ravit & Weis, 2014; Torok et al., 1996). Similar offset mechanisms have subsequently emerged internationally through biodiversity offsetting, habitat banking, stream mitigation, and ecological compensation programs, reflecting a broader shift toward market-based approaches for balancing development with environmental conservation (Coggan et al., 2013; Fernandez & Karp, 1998; Levrel et al., 2017; M. M. Robertson, 2004).

Although compensatory mitigation has evolved considerably, questions remain regarding its ecological effectiveness and long-term sustainability. Numerous investigations have demonstrated that restored or created wetlands often require decades to recover ecosystem structure and function and may never fully achieve the ecological integrity of reference wetlands (Bruland & Richardson, 2005; Matthews et al., 2009; Moreno-Mateos et al., 2012; Spieles, 2005). Research has increasingly emphasized the importance of hydrological restoration, soil development, vegetation succession, habitat complexity, and functional assessment as determinants of mitigation success (Ahn & Peralta, 2009; Deberry & Perry, 2015; Dee & Ahn, 2012; Hernandez et al., 2024; Stefanik & Mitsch, 2012). At the same time, policy-oriented studies have highlighted continuing challenges associated with mitigation banking, credit calculation, regulatory compliance, ecosystem valuation, and monitoring standards (Bryzek et al., 2024; Doyle & Yates, 2010; Hahn & Richards, 2013; M. Robertson, 2009; Stephenson & Tutko, 2018).

Recent years have witnessed a substantial expansion in research addressing wetland and waterways mitigation from multiple disciplinary perspectives. Advances in geographic information systems (GIS), remote sensing, ecological modeling, environmental economics, biodiversity assessment, and decision-support methodologies have broadened the scope of mitigation science beyond traditional ecological restoration. Emerging studies increasingly incorporate ecosystem service valuation, climate change adaptation, flood regulation, landscape connectivity, biodiversity offset markets, and spatial prioritization into mitigation planning and evaluation (Adusumilli, 2015; Buck et al., 2025; Chiavacci & Pindilli, 2020; Jessop et al., 2015; Wu et al., 2023). Consequently, the research domain has become highly interdisciplinary, involving environmental scientists, ecologists, hydrologists, surveyors, engineers, economists, planners, and policy analysts.

Despite the rapid growth, the intellectual development of wetland and waterways mitigation research has not been comprehensively synthesized. Existing review studies have primarily focused on specific aspects of mitigation, including ecological restoration, biodiversity offsets, mitigation banking, ecosystem services, or regulatory effectiveness (Coralie et al., 2015; Froger et al., 2015; Hrabanski, 2015; Lave, 2018). While these reviews provide valuable thematic insights, they generally rely on conventional narrative or systematic review approaches and do not quantitatively examine the structural evolution of scientific literature. Consequently, limited attention has been given to identifying how research themes have evolved over time, which topics have emerged or declined, how thematic relationships have changed across successive periods, and which research fronts currently dominate the field.

Bibliometric science mapping offers a robust framework for addressing these limitations by quantitatively analyzing the intellectual structure, thematic evolution, and conceptual dynamics of scientific literature. Unlike traditional review methods, bibliometric approaches employ citation relationships, keyword co-occurrence networks, thematic clustering, and longitudinal science mapping to reveal hidden knowledge structures and emerging research trajectories. Among available bibliometric tools, SciMAT provides longitudinal thematic evolution analysis based on centrality and density measures, while VOSviewer facilitates visualization of collaboration networks and keyword co-occurrence patterns, enabling comprehensive exploration of research development across temporal periods.

Given the increasing importance of wetland and waterways mitigation for ecosystem conservation, infrastructure resilience, climate adaptation, and sustainable environmental management, a comprehensive bibliometric assessment is timely and necessary. Such an assessment can identify the dominant research themes that have shaped the field over the past three decades, reveal emerging scientific priorities, evaluate the maturity of research topics, and highlight knowledge gaps requiring further investigation. These insights are particularly valuable for researchers, practitioners, and policymakers seeking to improve mitigation planning, ecological restoration strategies, and evidence-based environmental decision-making.

Accordingly, this study presents a comprehensive bibliometric review of wetland and waterways mitigation research published between 1996 and 2026. Using SciMAT and VOSviewer, the study evaluates publication trends, thematic evolution, conceptual structures, scientific collaboration patterns, and emerging research directions. Specifically, the objectives are to (i) examine the temporal growth and scientific productivity of wetland and waterways mitigation research; (ii) identify the major thematic clusters and their evolution across four consecutive periods (1996-2002, 2003-2010, 2011-2018, and 2019-2026); (iii) analyze the intellectual structure and collaboration networks within the research field; and (iv) identify emerging research opportunities that can guide future studies and support sustainable wetland and waterways mitigation policy and practice.

2. Materials and Methods

2.1 Research Design

This study employed longitudinal bibliometric review to examine the scientific development, intellectual structure, and thematic evolution of research on wetland and waterways mitigation over a thirty-one-year period (1996-2026). Bibliometric analysis has become an established quantitative approach for synthesizing large bodies of scientific literature by combining publication performance indicators with science mapping techniques to reveal the evolution of research themes, conceptual structures, and scholarly collaborators. Unlike traditional narrative reviews, bibliometric approaches provide objective and reproducible evidence of knowledge development while identifying influential research topics, emerging trends, and future research directions (Cobo et al., 2012; Donthu et al., 2021).

To obtain both thematic and network perspectives of the research field, this study integrated SciMAT and VOSviewer. SciMAT was employed to investigate thematic evolution, strategic thematic development, longitudinal relationships among research themes, and knowledge continuity across successive time periods. VOSviewer complemented these analyses by visualizing collaboration networks among authors, organizations, and countries, together with citation relationships that characterize the scientific influence and connectivity of the research community. The integration of these complimentary bibliometric platforms enabled a comprehensive assessment of both the conceptual and collaborative evolution of wetland and waterways mitigation research.

2.2 Data Collection and Literature Search Strategy

Scientific publications were retrieved from the Web of Science Core Collection and Scopus databases because both provide high-quality bibliographic metadata widely used for bibliometric investigations. Using multiple databases improves literature coverage while reducing database-specific bias and increasing the robustness of bibliometric analyses (Mongeon & Paul-Hus, 2016). Database searches were conducted on June 13, 2026, using predefined search strings developed to capture studies addressing wetland mitigation, stream mitigation, mitigation banking, compensatory mitigation, and aquatic resource mitigation.

The Web of Science search employed the topic query:

TS=((wetland* OR stream* OR river* OR waterway*) AND ("compensatory mitigation" OR "wetland mitigation" OR "stream mitigation" OR "mitigation banking" OR "mitigation bank*"))

The search was restricted to publications indexed between 1996 and 2026, written in English, and classified as Articles or Review Articles, yielding 459 records.

The Scopus search used:

TITLE-ABS-KEY(("wetland mitigation" OR "stream mitigation" OR "mitigation banking" OR "mitigation bank*" OR "compensatory mitigation" OR "aquatic resource mitigation"))

Additional filters limited the search to publications between 1996 and 2026, document type Article, and English-language publications, resulting in 413 records.

Combining both databases produced 872 publications. Duplicate records were removed using Zotero reference management software, leaving 536 unique publications for screening. Title and abstract screening excluded studies outside the scope of wetland and waterways mitigation, resulting in the removal of 99 publications. The remaining 437 publications constituted the final dataset for bibliometric performance analysis and science mapping using SciMAT and VOSviewer. The complete literature identification and screening procedure is illustrated in the PRISMA flow diagram Figure 1.

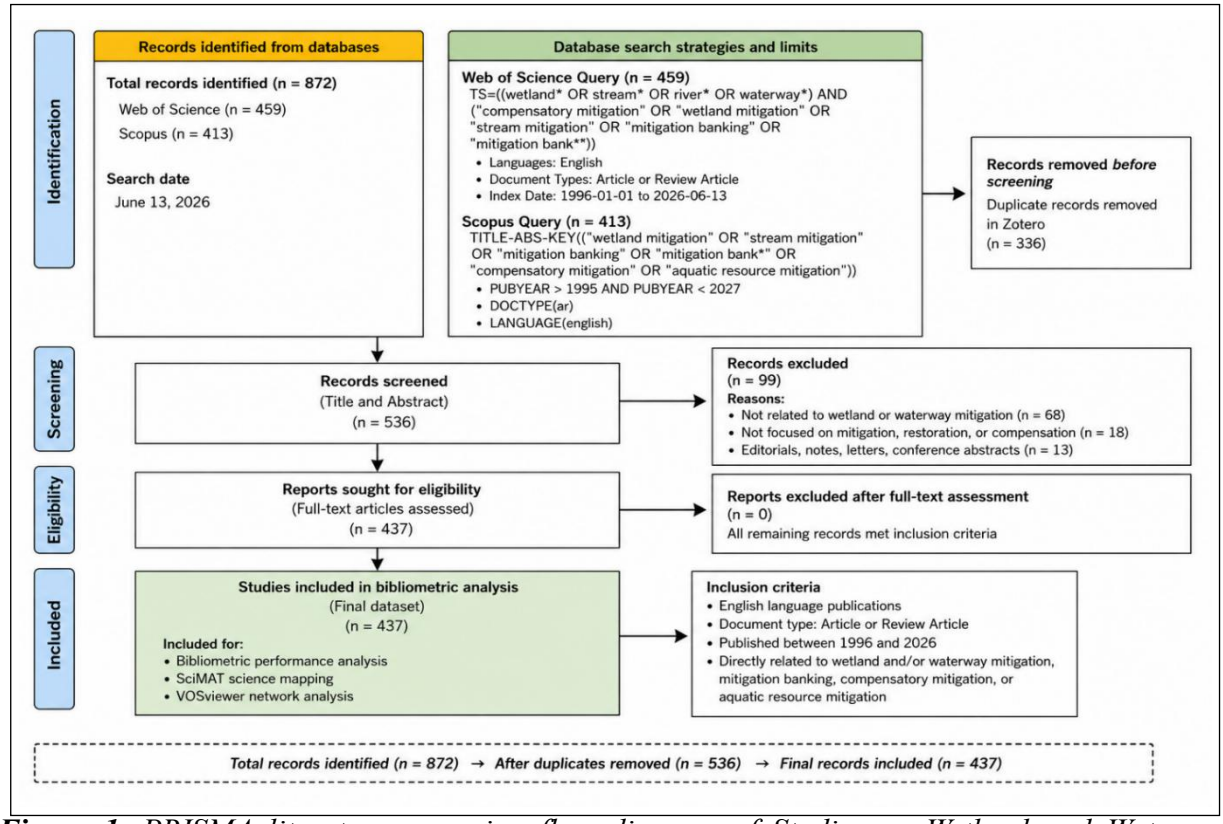

Figure 1. *PRISMA literature screening flow diagram of Studies on Wetland and Waterways Mitigation (1996-2016).*

2.3 Bibliometric Analysis Workflow

The bibliometric workflow consisted of four sequential stages. First, bibliographic records were retrieved from Web of Science and Scopus using predefined search strategies. Second, duplicate publications were removed, and the remaining records were screened according to predefined eligibility criteria. Third, the cleaned bibliographic dataset was exported into SciMAT and VOSviewer for complementary bibliometric analyses. Finally, thematic evolution, strategic diagrams, overlap analyses, collaboration networks, citation structures, and scientific performance indicators were synthesized to characterize the historical development and current research landscape of wetland and waterways mitigation.

To evaluate the temporal evolution of the research field, the dataset was divided into four consecutive periods representing distinct stages of scientific development: Period I (1996-2002); Period II (2003-2010); Period III (2011-2018); and Period IV (2019-2026). This temporal segmentation ensured adequate publication representation within each interval while allowing the evolution of research themes to be examined over time. SciMAT enables longitudinal analysis by dividing the study period into consecutive time intervals and examining thematic continuity, emergence, and disappearance through co-word analysis (Cobo et al., 2012).

2.4 SciMAT Science Mapping

SciMAT (Science Mapping Analysis Tool) was employed to investigate thematic evolution and conceptual development across the four study periods. Keyword-based co-word analysis was performed using author keywords, source keywords, and added keywords to maximize thematic representation throughout the dataset.

Prior to network construction, keyword reduction was performed by retaining terms with a minimum frequency of two occurrences. Co-occurrence matrices were generated to quantify relationships among research themes, while edge-value reduction with a minimum threshold of one was applied to eliminate weak associations. The Equivalence Index was selected as the normalization measure because of its effectiveness in representing conceptual relationships between research themes.

Research themes were identified using the Simple centers clustering algorithm with a maximum network size of forty keywords. Core mapper was employed to visualize thematic relationships, whereas the g-index and total citation count were selected to evaluate scientific performance and thematic influence. Theme evolution across successive periods was examined using the Jaccard similarity index, while conceptual continuity and keyword inheritance were evaluated using the Inclusion index through SciMAT's overlapping map. Table 1 shows the SciMAT parameters.

Table 1. *SciMAT parameter settings*

Parameter	Selected options
Unit of analysis	Author's words, Source's words, Added words
Data reduction	Frequency reduction, Minimum frequency (2) for all periods
Kind of matrix	Co-occurrence
Network reduction	Edge value reduction, Minimum value (1) for all periods
Normalization	Equivalence index
Clustering algorithm	Simple centers algorithm, Max. size (40), Min. size (1)
Document mapper	Core mapper
Evolution measure	Inclusion index
Quality measure	g-index, Sum citations
Longitudinal map	Evolution map (Jaccard's index), Overlapping map (Inclusion index)

2.5 VOSviewer Network Visualization

VOSviewer constructs bibliometric networks based on citation, co-authorship, bibliographic coupling, co-citation, and keyword co-occurrence relationships (Van Eck & Waltman, 2010). For this study, VOSviewer was used to complement the thematic analyses by constructing bibliometric networks that describe patterns of scientific collaboration and citation within the field. The analyses included collaboration networks among authors, research organizations, and countries, together with citation analyses of organizations and individual publications.

The network visualizations generated using VOSviewer enabled identification of influential researchers, leading institutions, international collaboration patterns, and highly cited publications

contributing to the advancement of wetland and waterways mitigation research. These complementary analyses provide additional insight into the social and intellectual structure of the research domain beyond the thematic evolution captured by SciMAT.

2.6 Bibliometric Indicators

The scientific development of the research field was evaluated using both performance analysis and science mapping indicators. Performance indicators included publication output, citation frequency, scientific productivity, and thematic impact measured through the g-index and cumulative citations. Science mapping indicators focused on strategic theme development, thematic centrality and density, conceptual continuity, thematic evolution Figure 2, and knowledge overlap across the four study periods. Together, these indicators provide a comprehensive understanding of the maturity, influence, and future direction of wetland and waterways mitigation research.

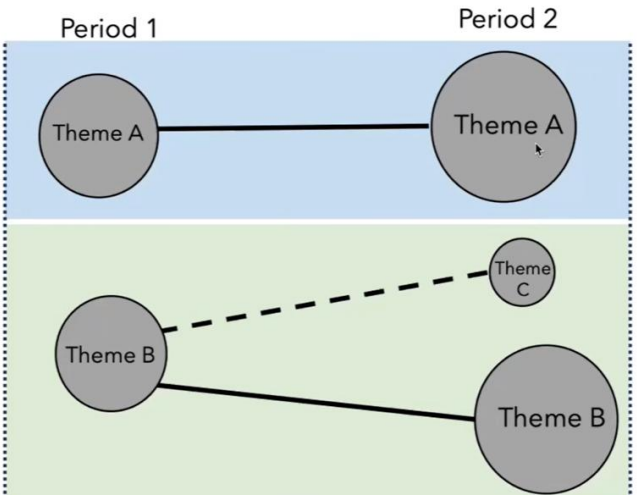

Figure 2. *Sample thematic evolution of themes (conceptual illustration).*

Strategic diagrams generated by SciMAT Figure 3 classified research themes according to two indicators: *Centrality*, representing the degree of interaction between a theme and other research themes, and *Density*, representing the internal development and maturity of each theme. Based on these indicators, themes were categorized as motor themes, basic and transversal themes, emerging or declining themes, and highly developed but isolated themes.

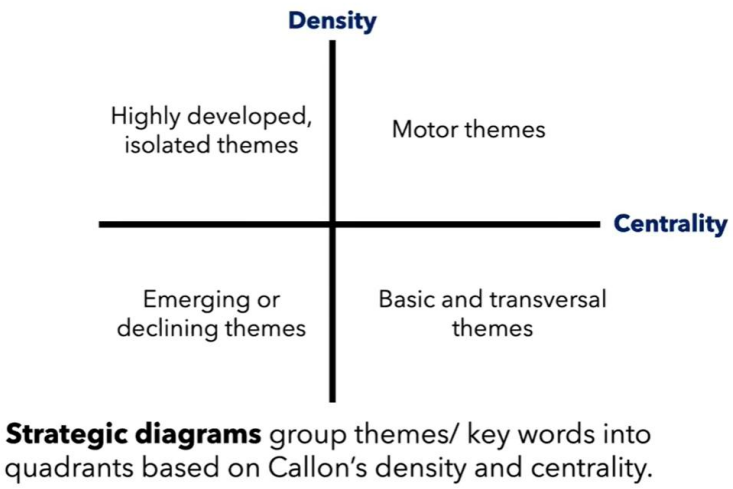

Figure 3. *Sample strategic diagram illustrating theme positioning.*

3. Results and Discussion

3.1 Publication Trends and Growth of the Literature

The temporal distribution of publications demonstrates the progressive expansion of research on wetland and waterways mitigation over the past three decades Figure 4. Following the adoption and maturation of compensatory mitigation policies in North America during the mid-1990s, scientific output increased steadily as researchers evaluated the ecological effectiveness of wetland restoration, mitigation banking, stream compensation, and regulatory implementation. The final bibliometric dataset Table 2 comprised 437 publications, which were analyzed across four consecutive periods to investigate the evolution of research themes and scientific knowledge.

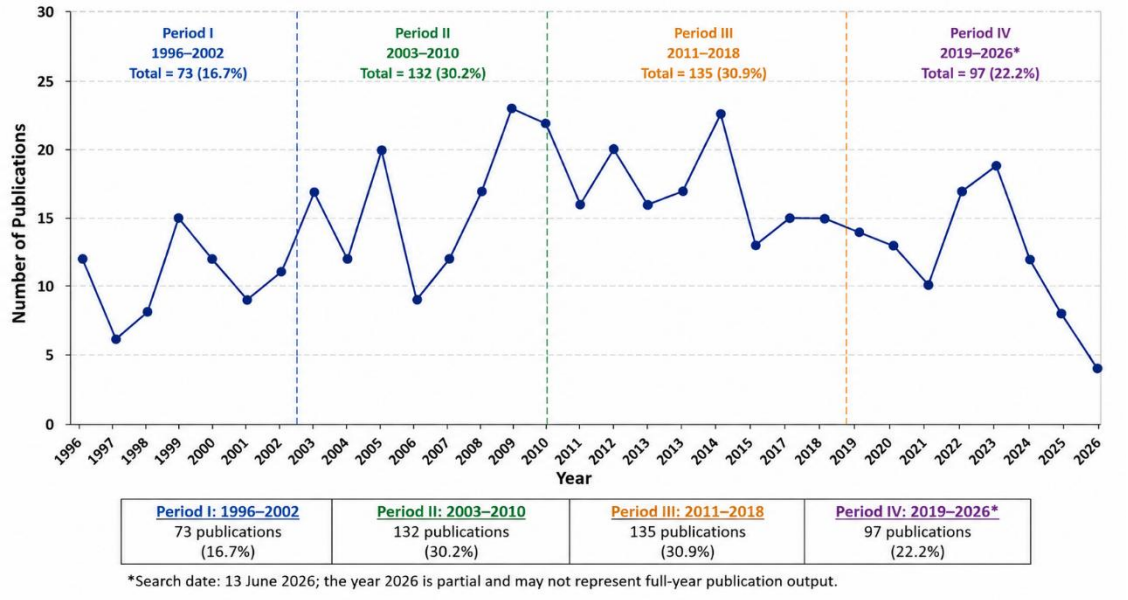

Figure 4. *Temporal distribution of publications (1996-2026).*

Table 2. *Distribution of publications across the four study periods.*

Period	Years	Publications
I	1996–2002	73
II	2003–2010	132
III	2011–2018	135
IV	2019–2026	97
Total		**437**

During the first study period (1996-2002), 73 publications were identified, representing the formative stage of the field. Research during this period primarily concentrated on establishing regulatory frameworks, evaluating mitigation compliance, documenting restoration practices, and assessing early ecological responses following wetland creation or enhancement. Much of literature focused on determining whether compensatory mitigation successfully replaced lost wetland functions while supporting biodiversity conservation and ecosystem recovery (Allen & Feddema, 1996; Burgin, 2010; Hornyak & Halvorsen, 2003; Pezzati et al., 2018; Zedler, 2004).

Research activity accelerated substantially during 2003-2010, when the number of publications nearly doubled to 132. This increase coincided with growing international attention to mitigation banking, ecological assessment methodologies, ecosystem service valuation, and performance monitoring. Increasing emphasis was placed on ecological effectiveness, long term monitoring, and decision support for mitigation planning, particularly following important regulatory developments such as the United States Compensatory Mitigation Rule introduced toward the end of this period (Kaplowitz et al., 2008; Pontius, 2008; Rubec & Hanson, 2009).

The highest research productivity occurred during 2011-2018, comprising 135 publications. This period reflects the maturation of the discipline, characterized by broader integration of landscape ecology, biodiversity conservation, spatial analysis, ecosystem services, and environmental decision-support tools. Advances in geographic information system (GIS), remote sensing, and ecological modeling also became more incorporated into mitigation assessment and planning, enabling more comprehensive evaluation of restoration performance across multiple spatial scales (S.-W. Kim et al., 2011; Nielsen et al., 2012; Nizamani et al., 2024; Sivakumar & Ghosh, 2016).

The final period (2019-2026) contained 97 publications. Although numerically lower than the preceding interval, this should not be interpreted as reduced scientific interest because the search concluded on 13 June 2026, resulting in an incomplete final publication year. Instead, research during this period demonstrates a clear transition toward restoration effectiveness, ecosystem resilience, climate adaptation, nature-based solutions, environmental impact assessment, and quantitative evaluation of ecological outcomes. Recent studies repeatedly emphasize functional restoration, biodiversity recovery, ecosystem service provision, and evidence-based mitigation planning using integrated ecological and geospatial approaches (Bryzek et al., 2023; Oliveira et al., 2026; Price et al., 2019; M. Robertson et al., 2021; Theis & Poesch, 2024).

3.2 Overlapping Analysis and Thematic Evolution in SciMAT

The overlapping analysis provides insight into the continuity and evolution of the research vocabulary across consecutive periods by examining the extent to which keywords are retained, introduced, discontinued over time. Unlike publication trend analysis, which reflects research productivity, overlapping analysis evaluates the conceptual development of a scientific field by measuring the persistence and emergence of research topics. SciMAT computes this evolution using the *inclusion index* and visualizes the relationships among successive periods through overlapping map Figure 5a and thematic evolution map Figure 5b, thereby revealing both the stability of mature research areas and the emergence of new scientific directions (Cobo et al., 2012).

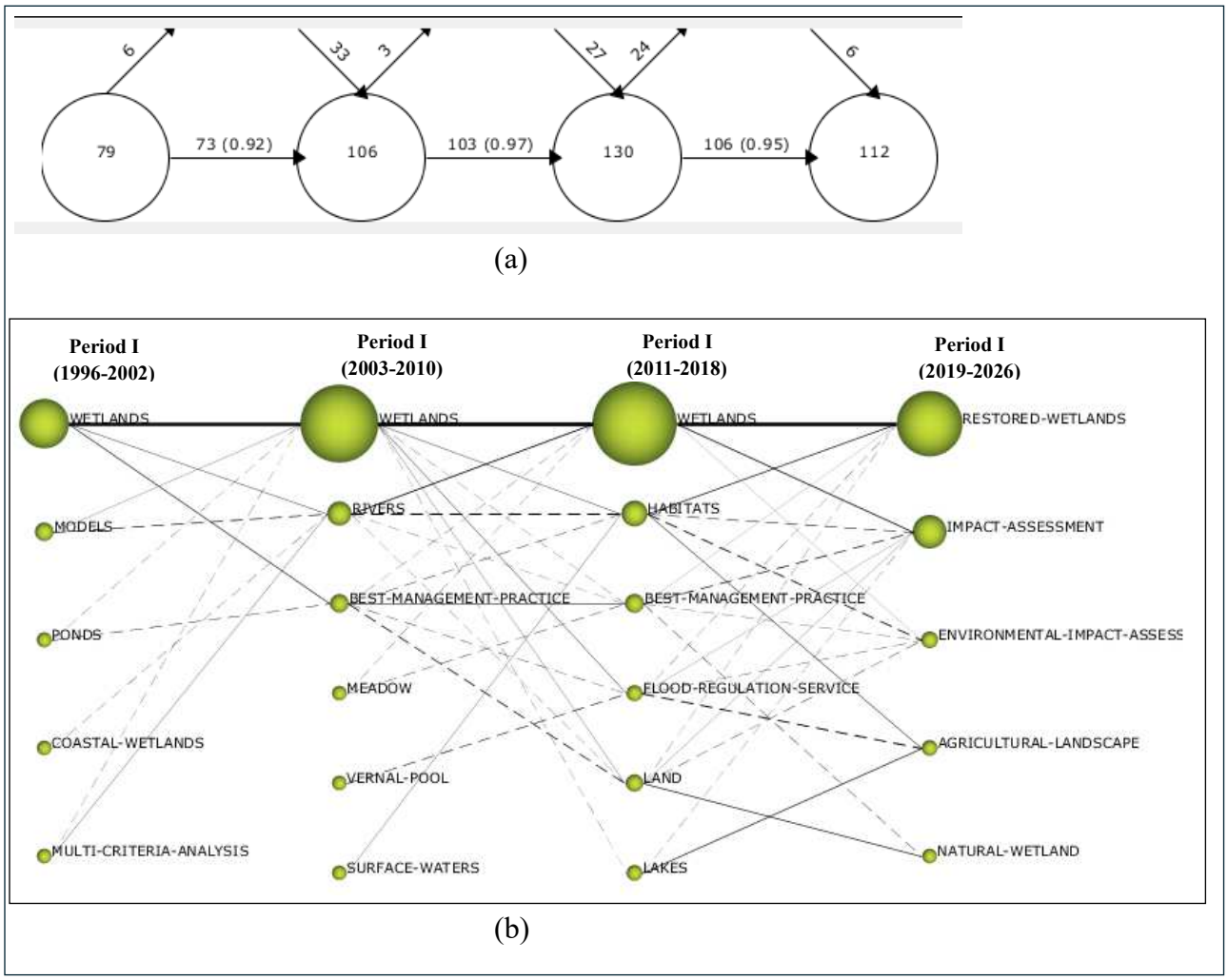

Figure 1. *SciMAT (a) Overlapping map (b) Thematic evolution maps of research themes (1996-2026)*

The wetland and waterways mitigation literature exhibited a progressive expansion of its conceptual structure throughout the four study periods Table 3. The number of identified themes

increased from 79 during 1996-2002 to 106 in 2003-2010 and further to 130 in 2011-2018 before slightly declining to 112 during 2019-2026. Although the final period contained fewer themes just as in publications than in the preceding period, the thematic network became more specialized, reflecting the consolidation of established research domains alongside the emergence of highly focused topics related to ecological restoration, impact assessment, biodiversity conservation, and environmental policy. Similarly, the overlapping analysis demonstrates a gradual increase in keyword continuity across successive periods. Early research was characterized by the introduction of numerous foundational concepts associated with wetlands, streams, rivers, mitigation banking, and ecological restoration. As the field matured, a larger proportion of keywords were retained between consecutive periods, indicating increasing conceptual stability. This pattern suggests that wetland and waterways mitigation research has evolved from establishing fundamental ecological and regulatory principles toward refining specialized assessment methods, ecosystem service valuation, restoration effectiveness, and market-based conservation mechanisms.

Table 3. *Summary of theme overlapping analysis.*

Period	Themes	Interpretation
1996–2002	79	Emergence of foundational concepts
2003–2010	106	Rapid thematic expansion
2011–2018	130	Highest thematic diversification
2019–2026	112	Consolidation into specialized research themes

The thematic evolution map Figure 5a further illustrates that “wetlands” remained the dominant and most persistent research theme throughout the entire study period, serving as the principal conceptual nucleus linking multiple emerging research areas. Strong evolutionary connections were observed between *wetlands* and subsequent themes including “rivers”, “habitats”, “restored-wetlands”, and “impact-assessment”, indicating that the scientific focus gradually expanded beyond wetland creation and compensatory mitigation toward watershed-scale ecosystem management, restoration performance evaluation, biodiversity conservation, and ecosystem service assessment. At the same time, new themes associated with climate change, environmental impacts, land management, and policy instruments became more connected to the core wetland mitigation literature, reflecting the interdisciplinary nature of contemporary mitigation research.

Above all, the overlapping analysis reveals a research domain that has transitioned from exploratory investigations into wetland mitigation practices during the late 1990s to a mature and interconnected body of knowledge characterized by stronger thematic continuity, increasing methodological sophistication, and broader integration of ecological, economic, hydrological, and policy perspectives. These findings provide the foundation for interpreting the strategic diagrams that will be presented in the subsequent sections, where the relative importance and maturity of individual research themes within each period are examined.

3.3 Strategic Diagram Analysis (1996-2002): Emergence of Foundational Research Themes

The first study period (1996-2002) represents the formative stage of wetland and waterways mitigation research, during which the scientific community established the ecological, hydrological, and regulatory principles that continue to underpin contemporary mitigation practice. The strategic diagram generated by SciMAT Figure 6 identified five principal themes "wetlands", "models", "ponds", "coastal-wetlands", and "multi-criteria-analysis." Together, these themes illustrate a research landscape primarily concerned with defining wetland functions, evaluating mitigation effectiveness, and developing analytical approaches for environmental assessment.

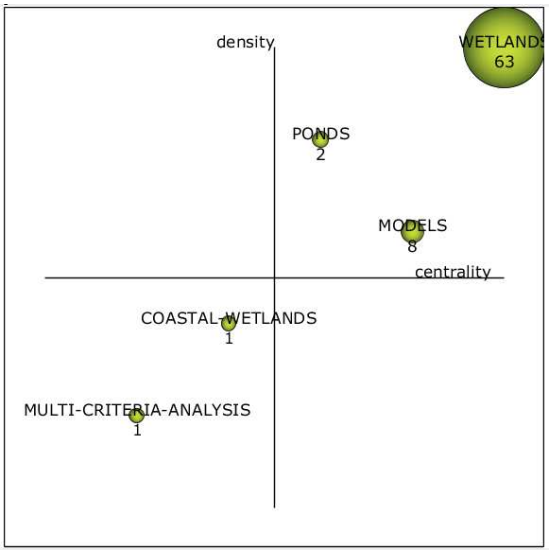

Figure 6. *Strategic diagram for the period 1996-2002.*

The strategic diagram evaluates each theme using two complementary indicators: "centrality", which measures the degree of interaction between a theme and the broader research field, and "density", which reflects the internal development and conceptual maturity of that theme (Callon et al., 1991; Cobo et al., 2012). Themes exhibiting high values for both indicators are regarded as motor themes because they are simultaneously well developed and strongly connected to the overall scientific domain.

Consistent with this interpretation, "wetlands" emerged as the domain motor theme during 1996-2002, recording the highest centrality (153.97) and density (76.09) among all identified clusters Table 4. Its prominent position demonstrates that research during this period was fundamentally organized around wetland ecosystem structure, ecological functions, restoration principles, and compensatory mitigation. The thematic network further confirms the extensive connectivity of the wetlands cluster with numerous associated concepts, including "ecosystem functions", "rivers", "riparian systems", "biodiversity", "vegetation", "soils", "drainage", "restoration", "assessment", "mitigation", "water resources", and "environmental management". Rather than representing a

single research topic, the “wetlands” cluster Figure 7a functioned as the intellectual hub linking ecological science, hydrology, environmental policy, and restoration practice.

Table 4. *Performance measures of themes during 1996-2002 generated by SciMAT*

Theme	Centrality	Density	Interpretation
Wetlands	153.97	76.09	Principal motor theme
Models	49.11	19.97	Emerging analytical theme
Ponds	44.64	37.50	Well-developed specialized theme
Coastal-Wetlands	18.82	19.44	Peripheral ecological theme
Multi-Criteria Analysis	17.94	12.50	Emerging decision-support theme

This strong thematic integration corresponds closely with the regulatory developments occurring during the late 1990s. Studies published during this period concentrated on establishing functional equivalence between impacted and restored wetlands, evaluating wetland ecosystem processes, and defining scientifically defensible mitigation criteria. Foundational investigations emphasized hydrogeomorphic assessment, ecological reference systems, hydrologic equivalence, mitigation banking, and no-net-loss policy implementation, thereby providing the conceptual basis for subsequent advances in wetland restoration and ecosystem service evaluation (Bedford, 1996; Brinson & Rheinhardt, 1996; Brown & Lant, 1999; Fernandez & Karp, 1998; Hauer & Smith, 1998).

The “ponds” cluster Figure 7b constituted the second most internally developed theme, exhibiting a density of 37.50 and a centrality of 44.64. Although substantially smaller than the wetlands cluster, its position indicates an established line of research focusing on constructed ponds, hydrological behavior, and aquatic habitat development within mitigation projects. Publications during this period progressively examined how water management influenced ecological succession, vegetation establishment, and habitat quality in restored aquatic systems, particularly in freshwater marshes and mitigation wetlands (Flynn et al., 1999; Hunt et al., 1998; Leck, 2003).

The “models” theme (centrality = 49.11; density = 19.97) occupied an intermediate position, indicating that analytical and predictive approaches were beginning to influence wetland assessment despite remaining at an early stage of conceptual development as shown in Figure 7c. Research during this period continuously explored ecological modeling, functional assessment frameworks, and decision-support methodologies to improve mitigation planning and environmental evaluation. Although modeling had not yet become a dominant research direction, its emergence foreshadowed the subsequent adoption of spatial analysis, ecosystem valuation, and decision-support systems that expanded considerably in later periods.

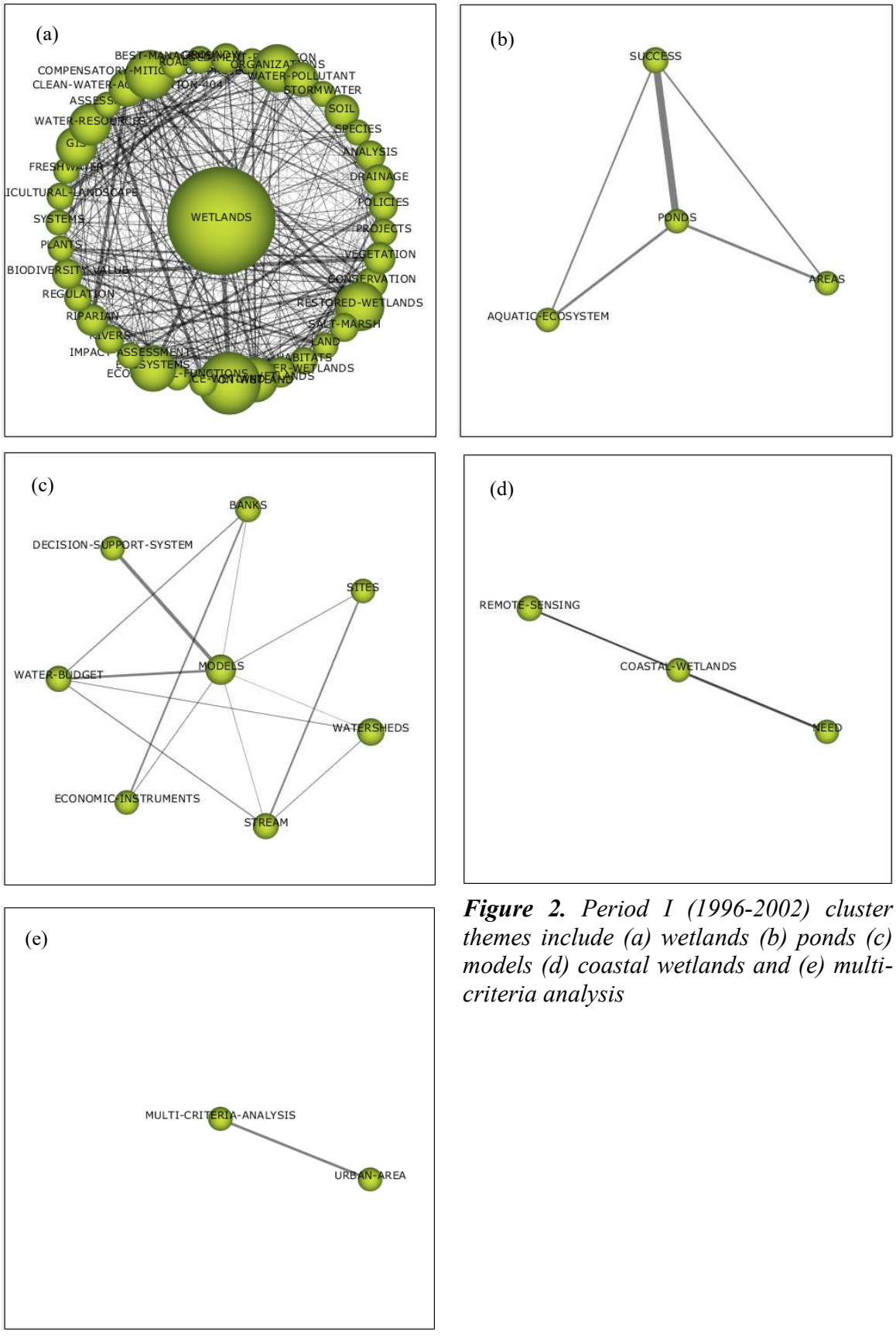

Figure 2. *Period I (1996-2002) cluster themes include (a) wetlands (b) ponds (c) models (d) coastal wetlands and (e) multi-criteria analysis*

In contrast, Figure 7d presented “coastal wetlands” (centrality = 18.82; density = 19.44) and “multi-criteria analysis” (centrality = 17.94; density = 12.50) Figure 7e appeared as relatively peripheral themes with limited interaction across the broader research network. Coastal wetland studies primarily addressed site-specific ecological restoration and hydrological processes, whereas multicriteria assessment remained in its infancy, reflecting early attempts to integrate multiple environmental variables into mitigation planning. Their comparatively low centrality suggests that these research directions had not yet become mainstream components of wetland mitigation science, although both would experience considerable expansion during subsequent decades as environmental decision-making became increasingly interdisciplinary.

Hence, the strategic diagram demonstrates that the first period was characterized by a highly centralized knowledge structure dominated by wetland ecology and restoration science. The prominence of the “wetlands” cluster indicates that researchers were primarily concerned with understanding ecological functions, defining restoration success, and establishing scientific principles capable of supporting compensatory mitigation policies. At the same time, the emergence of modeling approaches, pond ecosystems, and multicriteria assessment provided the conceptual foundations upon which later advances in ecosystem services, biodiversity conservation, restoration performance assessment, and spatial decision-support systems were subsequently developed.

3.4 Strategic Diagram Analysis (2003-2010): Expansion of Wetland Mitigation Research

The second period (2003-2010) represents a phase of substantial growth and rapid expansion in wetland and waterways mitigation research. During this period, the number of publications nearly doubled compared with the previous period, increasing from 73 to 132 publications Figure 4. This increase was accompanied by a broader thematic structure, reflecting the expansion of research beyond the foundational ecological principles established during the late 1990s. the SciMAT strategic diagram Figure 8 identified six principal themes “wetlands”, “rivers”, “best management practice”, “meadow”, “vernal pool”, and “surface waters”.



Figure 8. *Strategic diagram for 2003-2010.*

The strategic diagram indicates that "wetlands" remained the dominant motor theme of the research field, exhibiting the highest centrality (287.41) and density (86.33) among all identified clusters Table 5. Compared with the previous period, both indicators increased considerably, demonstrating that wetland-related research became not only more internally developed but also more strongly connected with other research themes. The enlarged cluster size further reflects the increasing volume of scientific publications addressing wetland restoration, ecological functions, vegetation development, hydrological processes, mitigation performance, and ecosystem management. This continued dominance illustrates that wetland ecosystems remained the primary scientific focus through which compensatory mitigation strategies were investigated and evaluated.

Table 5. *Performance measures of themes during 2003-2010 generated by SciMAT*

Theme	Centrality	Density
Wetlands	287.41	86.33
Rivers	188.26	29.32
Best-Management-Practice	79.83	24.91
Meadow	14.90	14.81
Vernal-Pool	15.61	8.33
Surface-Waters	11.32	8.33

The thematic network associated with the "wetlands" cluster Figure 9a further demonstrates the increasing complexity of the research landscape. Compared with the previous period, the network contains a wider range of interconnected concepts, indicating that wetland mitigation research had expanded beyond site establishment toward evaluating ecological condition, restoration effectiveness, and long-term ecosystem development. Studies published during this period steadily

evaluated restoration success using ecological indicators, habitat quality, biodiversity conservation, and landscape-scale ecosystem functions (Clare et al., 2011; K.-G. Kim et al., 2011; Spieles, 2005).

The “rivers” cluster emerged as the second motor theme, with relatively high centrality (188.26) and moderate density (29.32), indicating its growing importance within the overall knowledge structure. Unlike the broad ecological emphasis of the “wetlands” cluster, the thematic network for “rivers” Figure 9b concentrated on methodological and watershed-scale management issues. The strongest associations were observed with stream, watersheds, riparian systems, environmental impact assessment, hydric soils, resource management, remote sensing, statistical methods, sustainability and suitability, market-based approaches, and multi-criteria analysis. These relationships suggest that riverine mitigation research continuously emphasized watershed assessment, environmental evaluation, and decision-support methodologies capable of integrating ecological, hydrological, and spatial information for restoration planning. This trend corresponds well with studies advocating watershed-scale assessment frameworks and decision-support systems for mitigation planning (Nielsen et al., 2012; Rubec & Hanson, 2009).

The “best management practice” cluster occupied the upper-right quadrant as another motor theme, although with substantially lower centrality (79.83) and density (24.91) than the two dominant themes. The thematic network Figure 9c demonstrates that this cluster focused primarily on practical implementation strategies, connecting best management practice with drainage, sediment retention, aquatic ecosystems, agricultural landscapes, pollution control, offsetting, natural wetlands, and road infrastructure. These relationships reflect increasing attention to engineering and land-management interventions designed to minimize ecological degradation while improving restoration outcomes. During this period, best management practices became more integrated into mitigation planning as practical mechanisms for reducing environmental impacts associated with infrastructure and land development.

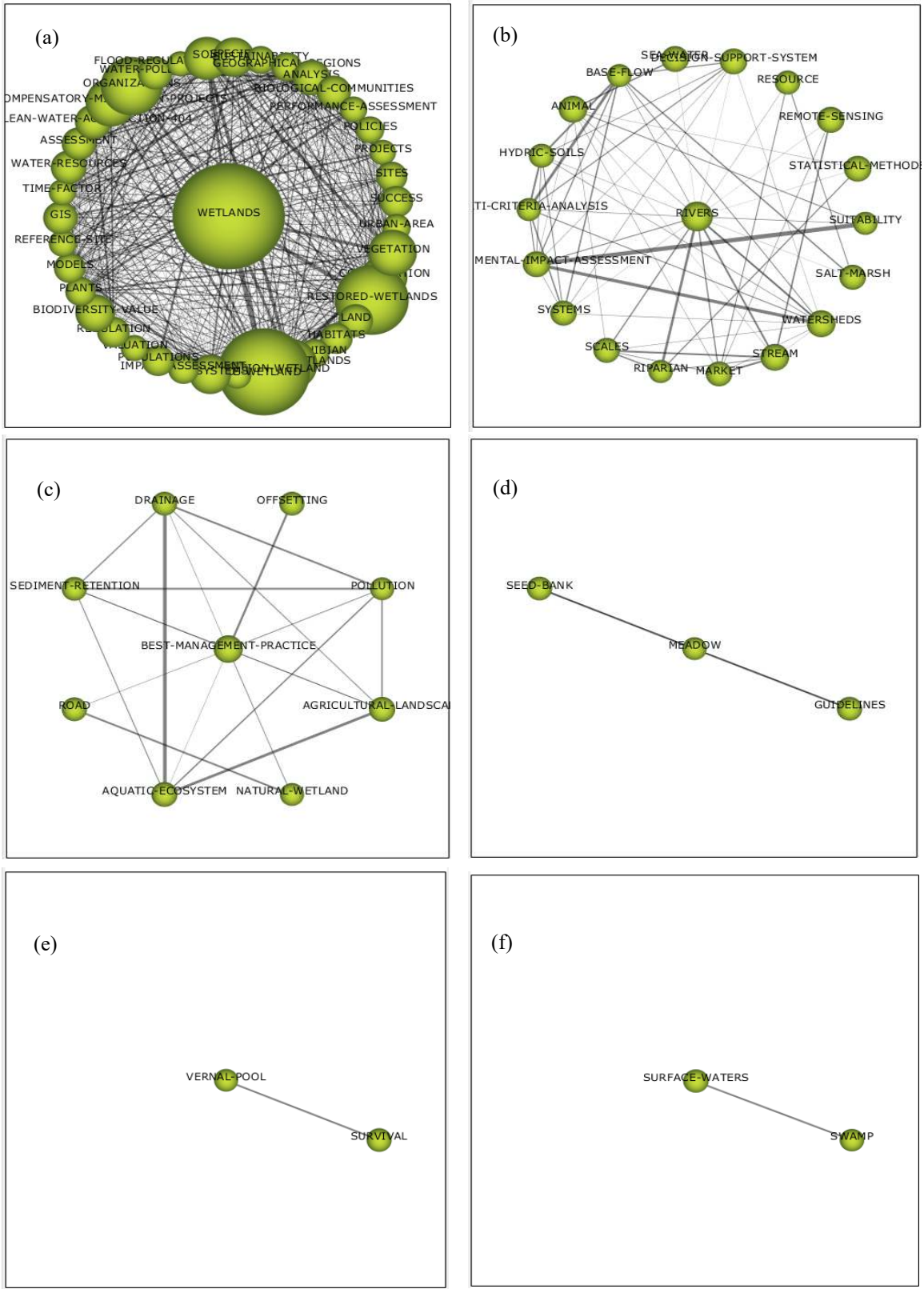

Figure 3. Period II (2003-2010) cluster themes include (a) wetlands (b) rivers (c) best management practice (d) meadow (e) vernal pool and (f) surface waters

The remaining themes occupied the lower quadrants of the strategic diagram and therefore represented relatively specialized or emerging research directions. The “meadow” cluster exhibited moderate centrality but relatively low density, indicating limited internal development despite few external connectivity. Its thematic network Figure 9d consisted only of meadow, seed bank, and guidelines, suggesting that research primarily addressed vegetation establishment and ecological restoration guidance rather than broader ecosystem interactions.

Similarly, “vernal pool” remained an emerging theme characterized by low density despite moderate centrality Figure 9e. the network contained only two closely connected concepts (vernal pool and survival) indicating that investigations were largely confined to species persistence and habitat survival within seasonal wetland ecosystems. Finally, “surface waters” appeared as a peripheral and week developed theme with the lowest centrality among all clusters (11.32). its network Figure 9f contained only a simple relationship between surface waters and swamp, suggesting that this topic had not yet matured into an integrated research domain during this period.

3.5 Strategic Diagram Analysis (2011-2018): An Improved Diversification of Wetland Mitigation Research

The 2011-2018 period represents a greater phase of thematic diversification in wetland and waterways mitigation research. Although “wetland” remained the dominant motor theme, several new research directions emerged that reflected growing interest in ecosystem services, habitat conservation, flood resilience, and landscape-scale environmental management. Compared with the previous period, the thematic structure became more heterogeneous, demonstrating that research had expanded beyond regulatory and mitigation compliance toward broader ecological and socio-environmental objectives.



Figure 4. *Strategic diagram for 2011-2018*

Consistent with the strategic diagram Figure 10, “wetlands” occupied the upper-right quadrant and exhibited the highest centrality (333.93) and density (88.57), confirming its position as the principal motor theme during this period Table 6. The thematic network Figure 11a illustrates that this cluster was strongly interconnected with numerous ecological and management concepts, including “restored wetlands”, ecological functions”, “ecosystem services”, “vegetation”, “watersheds”, “streams”, “habitats”, “biodiversity value”, “water pollution”, “remote sensing”, “soil”, “species”, “environmental impact assessment”, and “GIS”. These relationships inform that wetland mitigation research steadily emphasized ecosystem functionality rather than solely compensation for habitat loss. Studies during this period advanced in evaluating restoration effectiveness, ecosystem service provision, biodiversity conservation, watershed processes, and spatial assessment techniques, reflecting the growing integration of ecological science into mitigation planning (Price et al., 2019; M. Robertson et al., 2021).

Table 6. *Performance measures of themes during 2011-2018 generated by SciMAT*

Theme	Centrality	Density
Wetlands	333.93	88.57
Habitats	169.73	20.25
Best-Management-Practice	108.18	16.74
Flood Regulation Service	82.44	19.72
Land	72.35	7.4
Lakes	44.92	6.77

The second motor theme, “habitats”, demonstrated relatively high centrality (169.73) but moderate density (20.25), indication that habitat-related studies were becoming an important component of the broader mitigation literature while still undergoing conceptual development. As shown in its thematic network Figure 11b, the cluster connects habitat conservation with “riparian systems”, “amphibians”, “biological/animal communities”, “agricultural landscapes”, “decision-support systems”, “market-based instruments”, “resource management”, “standards”, and “ecosystem scales” among others. The emergence of these relationships reflects increasing recognition that successful mitigation requires consideration of landscape connectivity, ecological integrity, and species-specific habitat requirements rather than simple area replacement. These findings correspond with studies that evaluated biodiversity outcomes and ecological performance of mitigation and restoration projects across multiple habitat types (Bryzek et al., 2023; K.-G. Kim et al., 2011).

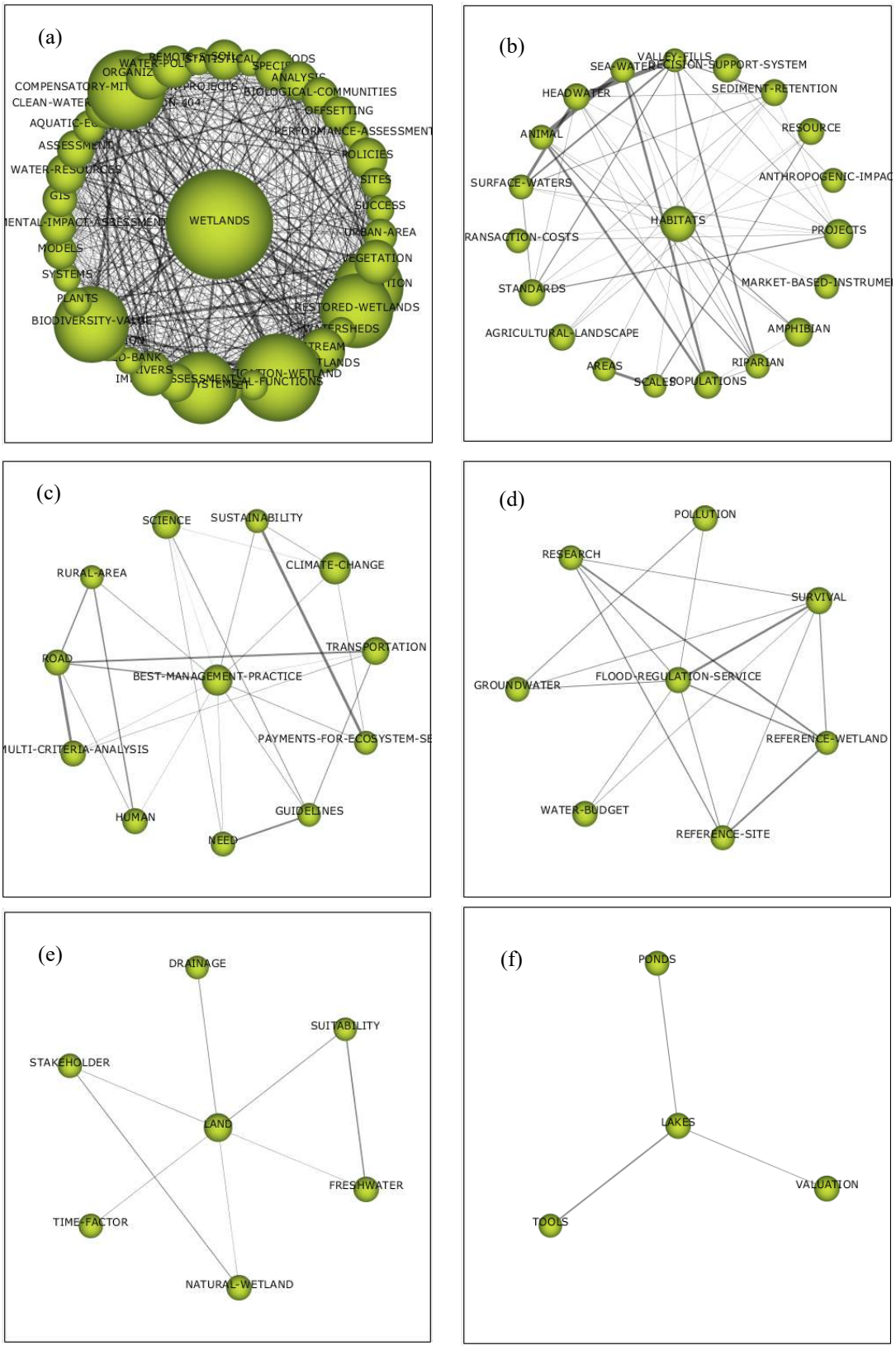

Figure 5. *Period III (2011-2018) cluster themes include (a) wetlands (b) habitats (c) best management practice (d) flood regulation service (e) land and (f) lakes*

Located close to the centrality axis, “best management practice” occupied an intermediate position between motor and basic themes (centrality = 108.18; density = 16.74). Its thematic network Figure 11c reveals strong associations with “multi-criteria analysis”, “road infrastructure”, “transportation”, “climate change”, “payments for ecosystem services”, “guidelines”, “sustainability”, and “science”. This network implies that mitigation research progressively incorporated integrated planning frameworks capable of balancing ecological, engineering, and policy objectives. The appearance of transportation infrastructure and multi-criteria decision analysis indicates a gradual transition toward decision-support approaches for evaluating mitigation alternatives within broader environmental management systems. Such developments are consistent with increasing adoption of ecosystem-based planning and integrated watershed management frameworks reported during this period (Nielsen et al., 2012).

Although “flood regulation service” manifests only moderate centrality (82.44), its comparatively higher density (19.72) insinuates that the theme had matured internally despite remaining less connected to the general knowledge structure. The thematic network Figure 11d links flood regulation with “groundwater”, “water budgets”, “pollution”, “reference wetlands”, “survival”, and “reference sites”, highlighting growing interest in the hydrological functions provided by restored wetlands. In preference to an exclusive focus on ecological replacement, research gradually investigated wetlands as nature-based infrastructure capable of reducing flood impacts, improving hydrological regulation, and enhancing watershed resilience. This thematic development foreshadowed the stronger emphasis on ecosystem services and climate adaptation that became evident during the subsequent period.

The lower-left quadrant contains “land” and “lakes”, both marked by relatively low centrality and density, suggesting that these themes remained peripheral within the entire research landscape. Nevertheless, their thematic networks in Figure 11e and Figure 11f provide insight into emerging research directions. The “land” cluster connects with “freshwater”, “drainage”, “natural wetlands”, “stakeholders”, “time factors”, and “suitability”, indicating localized investigations into land-use planning and site suitability for mitigation implementation. Similarly, the “lakes” cluster forms a compact network linking “ponds”, “tools”, and “valuation”, reflecting specialized research addressing lentic ecosystems and assessment methodologies instead of broad conceptual development.

It is therefore noted that the thematic landscape between 2011 and 2018 demonstrates an important transition from regulatory implementation toward ecosystem-based management. While wetland mitigation continued to provide the central organizing framework, increasing attention was devoted to habitat conservation, ecosystem services, flood regulation, landscape planning, and integrated decision-support approaches. This diversification established the conceptual foundation for the subsequent period, during which research continues to emphasize more restoration effectiveness, environmental impact assessment, and long-term ecological resilience.

3.6 Strategic Diagram Analysis (2019-2026): An Advanced Specialization and the Current State of Wetland Mitigation Research

The final period (2019-2016) comprised 97 publications and represents the most recent stage in the evolution of wetland and waterways mitigation research. Although the number of publications was lower than during 2011-2018 because the final period concludes in mid-2026 and not a complete eight-year span, the strategic diagram Figure 12 demonstrates continued thematic diversification and advanced specialization. Five principal themes were identified during this period which include “restored wetlands”, “impact assessment”, “environmental impact assessment”, “agricultural landscape”, and “natural wetland” Table 7. Compared with earlier periods, the emphasis shifted from establishing mitigation practices toward evaluating restoration performance, environmental impacts, ecosystem resilience, and long-term management outcomes.



***Figure 6**. Strategic diagram for 2019-2026*

***Table 7**. Performance measures of themes during 2019-2026 generated by SciMAT*

Theme	Centrality	Density
Restored Wetlands	365.4	92.37
Impact Assessment	228.59	23.53
Environmental Impact Assessment	108.7	36.42
Agricultural Landscape	77.49	7.25
Natural Wetland	22.94	8.33

“Restored Wetlands” emerged as the principal motor theme during this period, recording the highest centrality (365.40) and density (92.37). These values signify that restored wetlands became both the most influential and the most internally developed research topic within the field. The thematic network Figure 13a demonstrates an extensive knowledge structure linking restored wetlands with “biodiversity value”, “vegetation”, “habitats”, “streams”, “rivers”, “ecosystem

functions", "compensatory mitigation", "best management practices", "ecological assessment", "water resources", "GIS", "remote sensing", "species", "policies", "performance assessment", and "restoration success". Contrasted with previous periods, the network shows stronger integration of restoration monitoring with ecological performance evaluation, reflecting increasing attention to determining whether mitigation projects achieve long-term ecological objectives rather than merely satisfying regulatory requirements. Recent studies have advanced in emphasizing restoration trajectories, ecosystem functionality, and adaptive management as essential measures of mitigation effectiveness (Bryzek et al., 2023; Montemagni et al., 2026; M. Robertson et al., 2021).

"Impact Assessment" occupied the lower portion of the motor-theme quadrant, exhibiting high centrality (228.59) and demonstrate density (23.53). Figure 13b shows that this theme is closely associated with "sustainability", "climate change", "drought stress", "flood regulation services", "policy development", "urban areas", "land management", "market mechanisms", "environmental credits", "population dynamics", "regulation", "decision-support tools", and "multi-criteria analysis". The breadth of associated concepts illustrated how environmental impact assessment has evolved into multidisciplinary framework supporting planning, environmental governance, and restoration decision-making. Expanding integration of sustainability indicators, ecosystem service valuation, and climate adaptation reflects the broader transition from project-level mitigation assessment toward strategic environmental management (Garcia et al., 2025; Vaissière et al., 2017).

Also positioned in the upper-right quadrant, "environmental impact assessment" demonstrated moderate centrality (108.70) but relatively high density (36.42), indicating a mature but more specialized research domain. The thematic network Figure 13c ties environmental impact assessment with "stakeholder participation", "decision-support systems", "resource management", "woodland habitats", "survival", "spatial scales", and "scientific evaluation". These connections demonstrate an increased emphasis on integrating scientific evidence into environmental assessment processes while strengthening stakeholder involvement and decision support for restoration planning which is currently of more importance in the field. The prominence of decision-support systems further reflects the growing use of analytical frameworks to improve mitigation planning and evaluate restoration performance across multiple ecological and economic objectives.

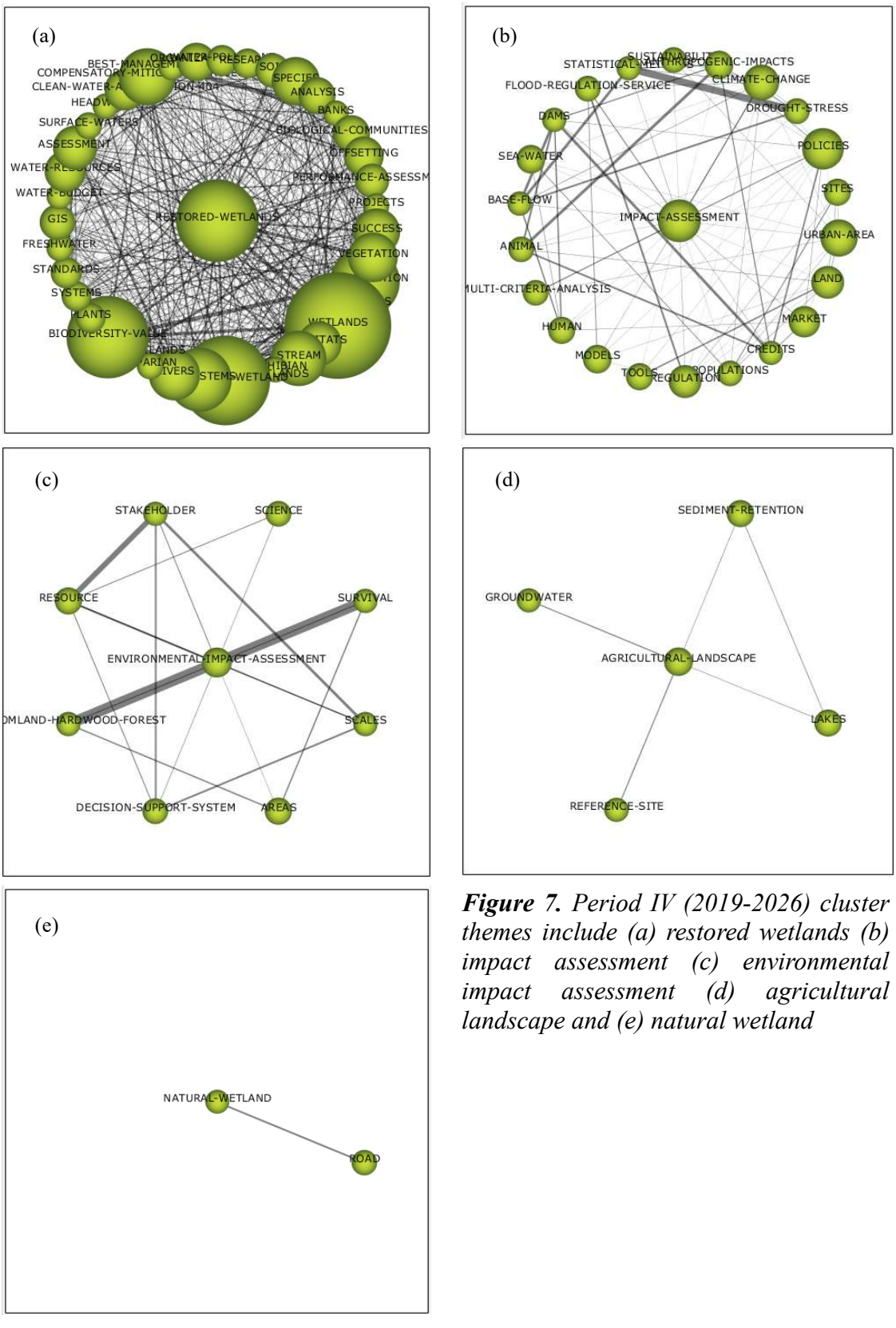

Figure 7. *Period IV (2019-2026) cluster themes include (a) restored wetlands (b) impact assessment (c) environmental impact assessment (d) agricultural landscape and (e) natural wetland*

“Agricultural Landscape” remained an emerging theme, described by moderate centrality (77.49) and relatively low density (7.25). as illustrated in Figure 13d, this cluster relates to “sediment retention”, “groundwater”, “lakes”, and “reference sites”, indicating that research gradually considered the interaction between agricultural land use and aquatic ecosystem restoration. The emergence of this theme reflects expanding interest in mitigating diffuse environmental pressures originating from agricultural landscapes while improving water quality and sediment control within compensatory mitigation programs. These findings are consistent with growing recognition that successful wetland restoration depends not only on site-specific interventions but also on broader watershed and landscape management strategies.

The final cluster, “natural wetland”, occupied the lower-left quadrant with the lowest centrality of 22.94 and a relatively low density of 8.33, which identify the theme as an emerging or highly specialized research topic. The thematic network Figure 13e contains only two connected sub-themes (natural wetlands and roads) suggesting that research at this stage explored the interaction between transportation infrastructure and naturally occurring wetland systems. Although still limited in scope, this emerging linkage reflects increasing interest in balancing infrastructure development with conservation of natural wetlands through environmentally sustainable planning and mitigation practices.

3.7 Bibliometric Collaboration and Citation Networks in VOSviewer

3.7.1 Author Collaboration Network

The author collaboration network generated in VOSviewer provides insight into the social structure of wetland and waterways mitigation research by identifying collaborative groups and influential contributors within the field. The network contained *55 authors* distributed across *eight collaboration clusters* Figure 14. Node size represents the number of publications associated with each author, while link thickness reflects the strength of co-authorship relationships.

The collaboration structure shows that *Mathews, J. W.* was the most prominent author in the network, with *17 documents, 28 links*, and the highest total link strength (TLS = 42). This indicates that Mathews occupied the strongest collaborative position in the author network and served as a major contributor to studies on wetland restoration, mitigation performance, and ecological assessment. Other highly connected authors included *Spyreas, G.* (5 documents; 10 Links; TLS = 14), *Kent, A. D.* (3 documents; 11 Links; TLS = 14), *Peralta, A. L.* (3 documents; 8 Links; TLS = 11), *Endress, A. G.* (3 documents; 7 Links; TLS = 9), *BenDor, T. K.* (7 documents; 8 Links; TLS = 9), and *Doyle, M. W.* (6 documents; 7 Links; TLS = 9). These authors represent key collaborative nodes within the research domain.

The network also reveals that collaboration is organized around several distinct research communities rather than a single fully integrated author network. The Mathews-centered cluster is strongly associated with restoration ecology, wetland vegetation, ecological assessment, and long-term mitigation performance. The BenDor’s and Doyle clusters reflect another important research

stream concerned with compensatory mitigation policy, stream mitigation markets, regulatory implementation, and the socio-economic dimensions of mitigation banking. The Robertson and Lave collaboration pathway appear to function as an important bridge between ecological restoration research and policy-oriented studies on stream and wetland mitigation markets. Hence, the strongest collaborations are concentrated around recurring co-author groups, while only a limited number of authors appear to connect separate clusters. This indicates a field with substantial expertise but moderate fragmentation, where ecological restoration, policy analysis, mitigation banking, and environmental assessment have developed as related but partly distinct research traditions.

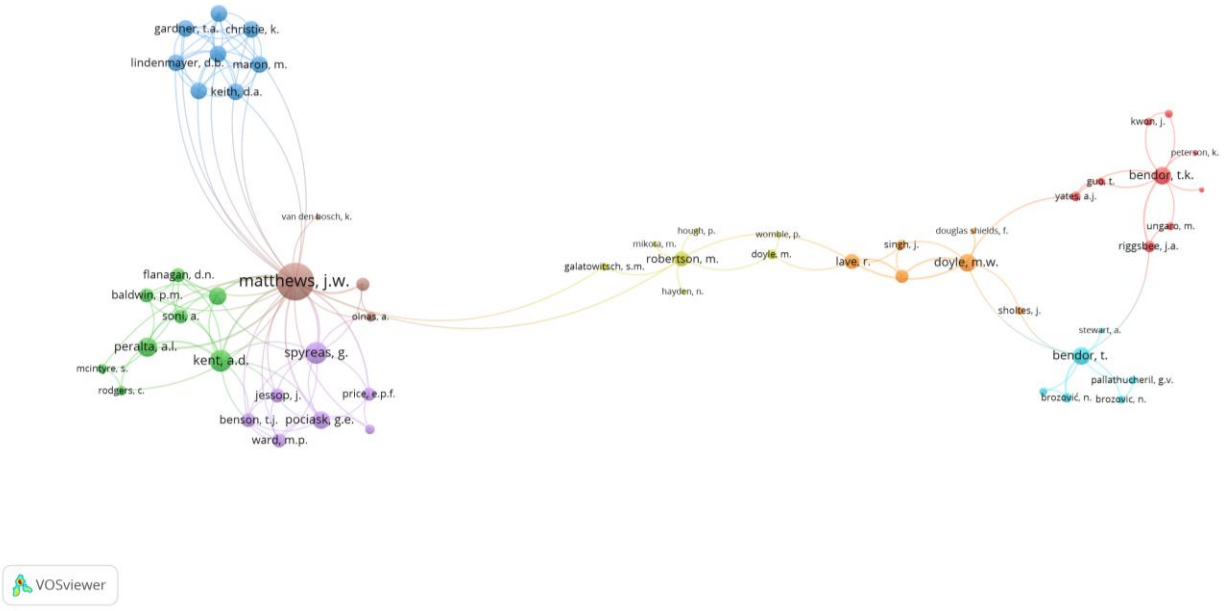

Figure 14. *Author collaboration network generated using TLS in VOSviewer*

3.7.2 Country Collaboration Network

The country collaboration network illustrates the geographical distribution of research partnerships in wetland and waterways mitigation and highlights the extent of international scientific cooperation within the field. The VOSviewer analysis identified several collaborating countries organized into distinct clusters Figure 15, indicating that although research has expanded internationally, collaboration remains concentrated among a relatively small number of countries. Node size reflects publication productivity, whereas link thickness represents the strength of collaborative relationships measured by Total Link Strength (TLS).

The *United States* emerged as the dominant contributor to the international collaboration network, recording the highest collaboration strength (TLS = 39) and the largest citation impact (12,885 citations). The country occupied a central bridging position connecting multiple collaboration clusters, demonstrating its pivotal role in advancing wetland mitigation research and facilitating international scientific exchange. This finding is consistent with the historical development of

compensatory mitigation policy in the United States, where regulatory frameworks established under Section 404 of the Clean Water Act have stimulated sustained research on wetland restoration, mitigation banking, and ecological performance assessment (Kaplowitz et al., 2008; Pontius, 2008).

Outside the United States, the *United Kingdom* represented the second most collaborative country (TLS = 15), followed by *Australia* (TLS = 12), *France* (TLS = 10), *Switzerland* (TLS = 9), Italy, The Netherlands, and *Spain* (each TLS = 8). These countries formed interconnected European and Commonwealth collaboration groups that contributed to studies on ecological restoration, environmental management, ecosystem services, and mitigation policy. Their relatively strong collaborative relationships suggest active knowledge exchange across regions addressing similar environmental and regulatory challenges.

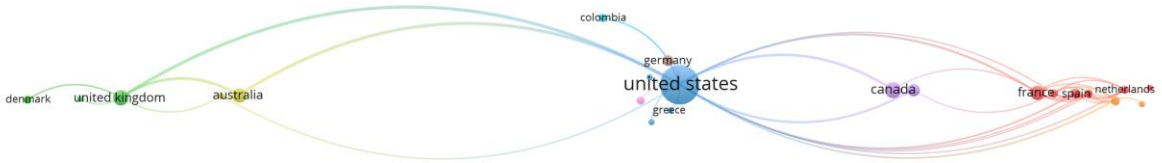

Figure 15. *Country collaboration network generated using VOSviewer*

The network also identifies several emerging contributors with comparatively lower contribution strengths, including *Canada* (TLS = 6), *China* (TLS = 5), *Colombia* (TLS = 3), and *Finland* (TLS = 3). Although these countries produced fewer collaborative links, their inclusion demonstrates the growing internationalization of wetland mitigation research beyond its traditional North American focus. The appearance of countries from Europe, Asia, South America, and Australia in Oceania region reflects increasing global recognition of wetland restoration as an important strategy for biodiversity conservation, climate adaptation, and sustainable water resource management. This collaboration network indicates that international research partnerships remain anchored by the United States while progressively expanding through regional collaborations in Europe and other parts of the world. The central bridging role of the United States, together with increasing participation from additional countries, suggests continued globalization of wetland and waterways mitigation research and an extensive dissemination of restoration practices, environmental assessment methods, and ecosystem management approaches.

3.7.3 Citation Analysis of Authors

The author citation network Figure 16 identifies the most influential researcher within the wetland and waterways mitigation literature based on citation relationships among the 437 publications included in this review. Unlike the collaboration networks presented previously, this analysis emphasizes scholarly influence by illustrating which authors have received the greatest citation impact and how their work is intellectually connected across the research domain. Table 8 shows the top 10 authors with highest citations.

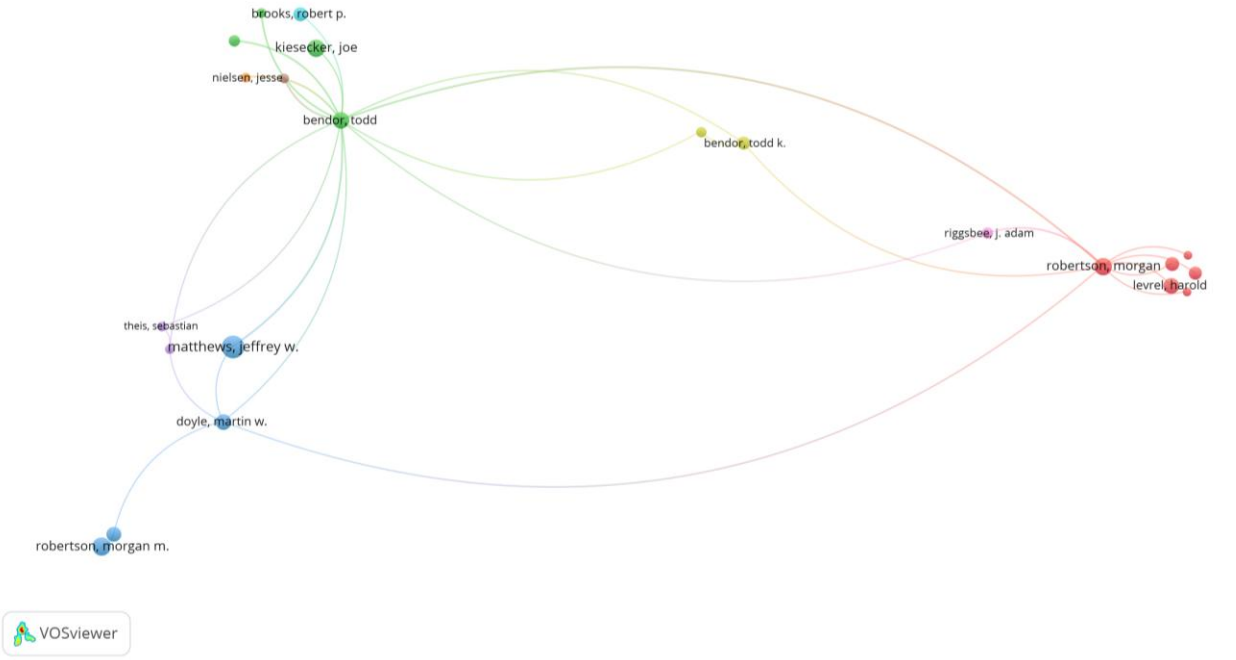

Figure 16. *Citation of Authors generated using VOSviewer*

Table 8*. Most influential authors based on citation analysis in VOSviewer.*

Author	Documents	Citations	Total Link Strength
Jeffrey W. Matthews	17	1,310	3
Morgan M. Robertson	3	524	1
Joe Kiesecker	2	367	1
Morgan Robertson	6	350	11
Todd Bendor	7	312	20
Martin W. Doyle	6	243	5
Harold Levrel	4	209	1
Rebecca Lave	4	195	2
Robert P. Brooks	3	146	1
Anne-Charlotte Vaissière	4	140	1

The network reveals several distinct citation clusters linked by a quite small number of highly cited authors. Among all authors, *Jeffrey W. Matthews* represents the most influential citation node, contributing 17 publications with 1,310 citations. Although his total link strength is comparatively

modest (TLS = 3), the exceptionally high citation count indicates that his work has become foundational to wetland restoration, mitigation practice, and ecological assessment. Matthews also serves as an important intellectual bridge connecting citation clusters through relationships with authors such as *Todd Bendor, Martin W. Doyle, Rebecca Lave, and Sebastian Theis*.

A second highly influential citation cluster is centered on *Morgan M. Robertson*, who accumulated 524 citations from three publications. Robertson's work forms a closely connected group with *Harold Levrel* and *J. Adam Riggsbee*, reflecting sustained scholarly attention to mitigation banking, ecosystem service valuation, and environmental policy. While this cluster contains fewer publications than that of Matthews, its high citation performance demonstrates its substantial theoretical influence within compensatory mitigation research.

Another major contributor is *Todd BenDor*, whose publications exhibit the strongest overall network connectivity. BenDor contributed seven publications, accumulated 312 citations, and recorded the highest total link strength (TLS = 20) among all authors. This combination indicates that his work is extensively connected with other influential researchers while maintaining considerable citation impact. The prominent position of BenDor with the network suggests that his studies have played an important role in integrating ecological restoration, mitigation banking, environmental economics, and planning into a cohesive body of literature.

Additional influential authors include *Martin W. Doyle* (243 citations), *Harold Levrel* (209 citations), *Rebecca Lave* (195 citations), *Robert P. Brooks* (146 citations), *Anne-Charlotte Vaissiere* (140 citations). Although these researchers differ in publication output and network connectivity, their citation performance demonstrates sustained contributions to topics including river restoration, ecosystem services, wetland managements, and environmental governance. The citation network therefore indicates that the intellectual development of wetland mitigation research has been shaped by a relatively small group of highly influential scholars whose publications continue to underpin subsequent investigations.

Following the temporal analyses, thematic evolution, strategic diagrams, thematic network structures, and bibliometric collaboration patterns, a comprehensive synthesis of the major research themes across the four study periods is presented in Table 9. The table consolidates the principal thematic developments identified through the SciMAT and VOSviewer analyses, highlighting the progression of research priorities from foundational wetland mitigation studies to contemporary restoration-oriented assessment frameworks.

Table 9. *Evolution of Dominant research themes across the four study periods*

Period	Dominant theme	Principal supporting themes	Research emphasis
1996–2002	Wetlands	Models; Ponds; Coastal Wetlands	Foundational ecological assessment and mitigation concepts

2003–2010	Wetlands	Rivers; Best Management Practice	Expansion toward watershed management and restoration practices
2011–2018	Wetlands	Habitats; Flood Regulation Service	Integration of ecosystem services and habitat conservation
2019–2026	Restored Wetlands	Impact Assessment; Environmental Impact Assessment	Evaluation of restoration outcomes and sustainability

4. Emerging Research Frontiers

The bibliometric evolution of wetland and waterways mitigation research reveals a progressive transition from studies primarily concerned with compensatory mitigation and ecological conservation toward broader frameworks that evaluate restoration effectiveness, ecosystem functionality, and long-term environmental sustainability. While early investigations established the ecological principles underpinning wetland mitigation, more recent research has steadily emphasized the assessment of restoration outcomes and the delivery of ecosystem services. This transition reflects the growing recognition that successful mitigation extends beyond habitat replacement to encompass ecological resilience, functional performance, and measurable environmental benefits under changing climatic and land-use conditions.

One of the most significant emerging directions is the increasing emphasis on evaluating restoration success through standardized assessment frameworks. The prominence of themes such as “Restored Wetlands”, “Impact Assessment”, and “Environmental Impact Assessment” in the most recent study period suggests that researchers are placing greater importance on quantifying ecological performance after restoration rather than simply documenting mitigation implementation. This evolution supports a shift toward evidence-based environmental management in which restoration projects are evaluated using ecological, hydrological, and socio-economic performance indicators that can inform adaptive management and policy refinement.

Another notable trend is the growing integration of ecosystem service concepts into wetland mitigation planning. Contemporary studies recognize more of the wetlands as multifunctional systems that provide flood attenuation, water quality improvement, biodiversity conservation, carbon storage, and climate adaptation benefits. Consequently, mitigation planning evolves from site-specific ecological restoration toward landscape-scale management that considers cumulative environmental functions and the interactions among wetlands, rivers, floodplains, streams, and surrounding ecosystems. This broader systems perspective has strengthened the scientific basis for prioritizing restoration investments and evaluating their long-term societal and environmental value.

The bibliometric analyses also indicate an increasing convergence of ecological science with environmental planning, decision-support methodologies, and sustainability assessment. As wetland mitigation projects become more complex and involve multiple stakeholders, future

research is expected to further integrate spatial decision-support tools, environmental modeling, geospatial analysis, and multidisciplinary evaluation approaches to improve mitigation planning and monitoring. Such developments have the potential to enhance transparency in environmental decision making while supporting more effective implementation of restoration policies across diverse ecological and regulatory settings.

5. Research Gaps and Future Directions

Despite the considerable expansion of wetland and waterways mitigation research, several important knowledge gaps remain. Although recent studies now emphasize restoration effectiveness and environmental assessment, relatively few investigations evaluate mitigation performance over sufficiently long temporal scales to capture ecosystem succession, hydrological stability, and functional recovery. Future research should therefore prioritize long-term monitoring programs capable of assessing the sustainability of restoration outcomes.

Another challenge is the lack of standardized frameworks and current technologies capable of predicting and evaluating wetland mitigations via multiple ecosystem functions simultaneously. Most existing studies assess vegetation establishment, biodiversity, hydrological performance, or ecosystem services independently, limiting direct contributions of factors and comparison among mitigation projects. Developing integrated evaluation frameworks and forecasting tools that combine ecological, hydrological, environmental, and socio-economic indicators would improve the consistency and transferability of mitigation forecasting and assessments.

The bibliometric analyses also reveal geographical disparities in research productivity and collaboration. Scientific contributions remain concentrated in North America and parts of Europe, while comparatively fewer studies originate from regions experiencing rapid wetland degradation and infrastructure expansion. Expanding international collaboration and increasing research efforts within underrepresented regions would improve the global applicability of mitigation science and knowledge sharing.

Future investigations should further integrate emerging geospatial technologies and digital decision-support tools into wetland mitigation research. Remote sensing, GIS, machine learning, geospatial artificial intelligence (GeoAI), and environmental modeling provide significant opportunities to improve wetland mitigation forecasts, site selection, restoration monitoring, impact assessment, and adaptive management. Strengthening interdisciplinary research that combines ecological science, environmental policy, economic valuation, and stakeholder participation will further support evidence-based mitigation planning and sustainable management of aquatic resources.

6. Conclusions

This study presented a comprehensive bibliometric review of wetland and waterways mitigation research published between 1996 and 2026 using an integrated science mapping approach based on SciMAT and VOSviewer. Analysis of 437 publications revealed sustained growth in scientific

output and a clear evolution of research priorities over four distinct periods. The thematic progression demonstrated a transition from foundational studies focused on wetland mitigation and ecological compensation toward broader research emphasizing restoration effectiveness, environmental impact assessment, and ecosystem-based management. The longitudinal perspective provided by SciMAT further illustrates the continuity, emergence, and transformation of major research themes that have shaped the field over the past three decades.

The collaboration and citation analyses in VOSviewer complemented the thematic evolution by identifying the principal contributors and intellectual structure of the research domain. The United States emerged as the leading contributor to international collaboration, while a relatively small number of influential authors played central roles in advancing knowledge on wetland restoration, mitigation banking, ecosystem services, and environmental policy. These findings demonstrate that the field has matured into an interdisciplinary area integrating ecological restoration, environmental planning, hydrology, economics, and conservation science to address many complex environmental challenges.

Findings of this review provide a valuable reference for researchers, practitioners, and policymakers seeking to understand the historical development and current direction of wetland and waterways mitigation research. By identifying dominant research themes, influential contributors, collaborative networks, and emerging priorities, this study establishes a foundation for future investigations aimed at improving restoration effectiveness, strengthening environmental assessment frameworks, expanding international collaboration, and supporting evidence-based mitigation strategies for the sustainable management of aquatic ecosystems.

Declarations: All authors have read, understood, and complied with the journal's statement on the "Ethical Responsibilities of Authors" as provided in the Instructions for Authors. The authors also acknowledge that, except in limited circumstances, changes to authorship cannot be made after manuscript submission.

Author contributions: Conceptualization: all authors; data curation, study design and methodology: M.O.O.; formal analysis: O.O. and M.O.O.; software: M.O.O.; supervision and validation: O.O. and B.F.S.; writing – original draft: all authors; writing – draft review and editing: all authors.

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