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Estuarine saltwater intrusion research needs to move beyond hazard assessment towards adaptation-ready evidence

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Abstract

Saltwater intrusion is increasingly affecting estuarine ecosystems, freshwater resources, agriculture and coastal communities under climate change, yet it remains unclear whether the growing evidence base is sufficiently developed to support adaptation. Here, we systematically synthesise 222 peer-reviewed studies published between 1996 and 2026 to evaluate how saltwater intrusion research has progressed from hazard assessment towards adaptation-ready evidence. Using an adaptation evidence maturity framework, we assess progression from evidence on drivers and impacts to management, adaptation and implementation. Saltwater intrusion research has expanded rapidly and is strongly concentrated on physical processes, numerical modelling and water-resource impacts. Although more than 95% of studies addressed drivers, impacts and affected systems, only 45% discussed management responses, 16% provided adaptation evidence and fewer than 1% documented implementation. Our synthesis reveals a persistent evidence-to-action gap: advances in hazard characterisation have not been matched by comparable progress towards adaptation evidence. We further synthesise a portfolio of adaptation responses and present a conceptual framework linking adaptation options to adaptation-ready evidence, highlighting the bottlenecks that limit the translation of hazard knowledge into evidence capable of supporting climate-resilient decision-making. Our findings provide a practical basis for identifying where evidence should progress from hazard and impact assessment towards adaptation, helping to prioritise research needed for climate-resilient estuarine management.

Introduction

Estuaries are transitional environments where freshwater and marine processes interact[1]. Saltwater intrusion is a natural feature of estuarine dynamics, but its extent, duration and intensity are increasingly being altered by sea-level rise, changing freshwater inflows, and interacting anthropogenic pressures[2–4]. Further penetration of saltwater upstream, prolonged persistence of saltwater, or increasing intensity of saline/brackish conditions may compromise freshwater availability[5], disrupt ecological communities[6], alter biogeochemical processes[7], and affect agriculture or infrastructure[8,9]. These consequences matter because estuaries support dense populations, critical infrastructure, food production, ecosystem services and long-standing cultural and livelihood connections, including those of Indigenous communities[10,11]. In these locations, climate change may result in a dynamic, rather than stationary, management problem[12]. As such, an important question remains whether the available scientific evidence on saltwater intrusion in estuaries is sufficiently developed to support adaptation decisions. Here, saltwater intrusion is considered broadly as the upstream, landward, lateral or vertical movement of marine salinity into fresher parts of estuarine and hydrologically connected coastal systems.

Over the past decades, saltwater intrusion research has advanced substantially via detailed observations, improved monitoring networks, and advanced analytical tools. Field campaigns and long-term salinity records have strengthened our understanding of temporal variability[13], extreme intrusion events[14], and the influence of river discharge, tides and drought on upstream salinity dynamics[15]. Hydrodynamic and coupled numerical models have further resolved estuarine circulation, salt-wedge behaviour[16], and the sensitivity of intrusion to changing channel geometry, freshwater inflows and sea-level rise[17–19]. Recently, geospatial techniques, machine learning and other data-driven approaches have expanded opportunities to monitor large and data-limited systems and to complement process-based modelling[20–22]. Climate projections are increasingly being integrated with hydrodynamic and salinity models to quantify potential changes in saltwater intrusion across regional and global scales, while ecological and physico-chemical studies have addressed consequences for water quality, habitats and ecosystem functioning[12,23]. Collectively, these advances have substantially improved our understanding of the processes, drivers and consequences of saltwater intrusion across a wide range of estuarine environments, creating a rich and rapidly growing evidence base. However, this knowledge has largely developed across partially disconnected physical, ecological and management domains[24]. The extent to which these individual domains have been integrated within individual studies, and whether greater integration produces more management-relevant evidence, remains poorly understood. As such, the primary challenge associated

with saltwater intrusion in estuaries is not simply the amount of available evidence, but how effectively that evidence progresses from risk assessment to management and adaptation.

Decision-relevant climate research typically follows a risk-to-adaptation pathway: characterising the hazard, quantifying potential impacts, identifying affected systems, defining possible responses, assessing their effectiveness and feasibility, and documenting implementation and monitoring outcomes to support learning and future decision-making[25,26]. These stages are analytically different; identifying sea-level rise or reduced river flow as a driver is not equivalent to quantifying consequences; similarly, mentioning management does not demonstrate that an adaptation option has been identified or implemented. Consequently, a large volume of literature describing a climate hazard does not inherently suggest an adaptation-ready evidence base[27]. Herein, we define adaptation-ready evidence as research that progresses beyond hazard or impact characterisation to support the identification, evaluation, implementation and monitoring of management and adaptation responses.

As climate risks intensify, the maturity of the evidence supporting adaptation becomes increasingly important. Whether saltwater intrusion research has advanced towards this end goal, and how evidence is distributed across risk identification, response assessment, implementation and monitoring, has not been systematically evaluated at the global scale. Previous studies and reviews have substantially advanced our understanding of saltwater intrusion across physical[28], ecological[29] and management[30] dimensions. Syntheses have investigated the roles of tides[31], sea-level rise[24], river discharge[32], channel modification and other anthropogenic pressures[33] in controlling intrusion within estuarine systems[34]. Complementary reviews have extended this process-based understanding by examining projected sea-level-rise effects, advances in modelling approaches and regionally variable climatic responses[24,35,36]. In parallel, coastal-aquifer reviews have synthesised groundwater intrusion processes, simulation-optimisation methods, monitoring approaches and groundwater-management strategies[37,38]. Ecological and system-specific syntheses have further considered impacts on fisheries, wetlands, agriculture, water supplies and estuarine ecosystem functioning[29,39–41]. Beyond these assessments, management-oriented reviews have examined responses within specific environments or intervention categories, including coastal wetlands and coastal aquifers[29,42]. Collectively, these previous reviews provide strong foundations within their respective domains. However, the extent to which individual studies integrate physical, ecological and management evidence, how far they progress along the risk-to-adaptation pathway, and where evidence gaps remain between understanding hazards and impacts and assessing, implementing and evaluating adaptation responses are still unclear. Consequently, it has not been systematically assessed which driver-impact-system relationships are linked to management and adaptation responses, or where evidence gaps persist

along the risk-to-adaptation pathway. In this context, research gaps are not equally consequential: a lack of evidence on adaptation effectiveness, feasibility, implementation or monitoring has more direct implications for decision-making than additional hazard characterisation in already well-studied systems.

Here, we systematically synthesise the peer-reviewed literature on saltwater intrusion in estuarine systems explicitly situated within climate-change and sea-level-rise contexts. Drawing on 222 primary studies published over the past three decades, we develop an adaptation evidence maturity framework to evaluate how saltwater intrusion research has progressed from understanding drivers and impacts towards management, adaptation and implementation. Specifically, we ask: (1) where is saltwater intrusion research concentrated and which forms of evidence dominate; (2) how well physical, ecological and management dimensions are integrated; (3) how far research has progressed along the risk-to-adaptation pathway; and (4) which pathways connect drivers and impacts to affected systems, management and adaptation responses? We organise the evidence for our analyses into a risk-to-adaptation pathway, identifying where interventions can reduce hazard, exposure and vulnerability, strengthen ecosystem resilience, and support monitoring and adaptive learning, while accounting for residual risk, co-benefits, trade-offs and maladaptation. Beyond synthesising the literature, this framework provides a structured approach towards diagnosing where evidence is concentrated, where gaps remain, and where future research is most needed to support adaptation. Overall, this study identifies critical bottlenecks between hazard identification and adaptation implementation, thereby helping to prioritise the evidence needed to support climate-resilient action on saltwater intrusion in estuaries under accelerating environmental change.

Results

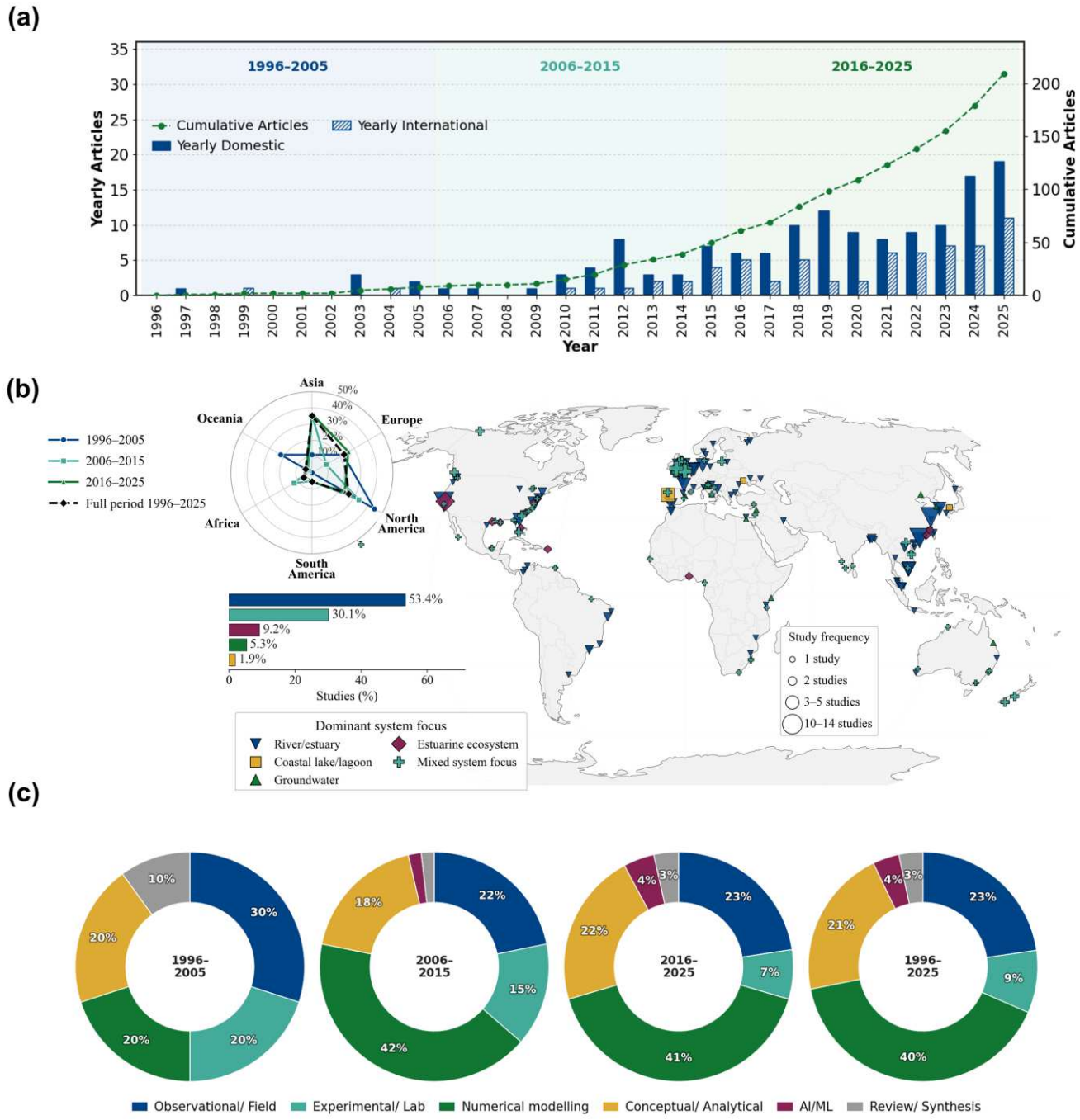
Growth, geographic distribution and methodological evolution

Saltwater intrusion research in estuarine environments increased substantially between 1996 and 2025, although publication growth was strongly concentrated in the most recent decade (Fig. 1a). Research was limited during 1996-2005, with several years producing no related studies and only occasional increases in annual publication numbers. It then increased gradually during 2006-2015, before accelerating after 2015. The number of studies published annually generally remained below ten until the late 2010s but increased substantially thereafter, reaching its highest levels in 2024 and 2025 (Supplementary Data 1). The recent growth accounted for most of the cumulative evidence base, with the cumulative number of studies rising rapidly after 2018. Publications involving authors affiliated with institutions in a single country (domestic studies) accounted for most studies throughout the review period. Publications involving authors from institutions in two or more countries (international studies) became more frequent during the most recent decade but remained less common in most years. This pattern indicates that the growth of saltwater intrusion research has occurred predominantly within single-country authorship networks, although international research collaborations have increased over time. Overall, these patterns demonstrate rapidly increasing scientific attention to saltwater intrusion under climate change, although knowledge generation has remained largely driven by domestic, rather than internationally coordinated research efforts.

The geographic distribution of research was highly uneven and clustered in particular regions (Fig. 1b; Supplementary Data 2). A total of 288 unique study sites were identified across six continents (Fig. 1b; Supplementary Data 2). These sites were derived from 480 study-location records from 206 of the 222 studies. For the 1996-2025 continental analysis, 194 studies were included. Each study was counted once within every continent in which it had at least one study site. Because some studies included sites in more than one continent, this resulted in 202 study-continent assignments across the six continents. Asia accounted for the largest share of these assignments (35.1%), followed by North America (26.2%) and Europe (22.8%). Africa, South America and Oceania together represented 15.8%, contributing 5.9%, 5.4% and 4.5%, respectively. Continental representation also changed over time. During 1996-2005, North America accounted for the largest share of study-continent assignments (44.4%), followed by Europe and Oceania (22.2% each) and Asia (11.1%). By 2006-2015, Asia had become the leading region, accounting for 35.9% of assignments, followed by North America at 33.3%. This pattern continued during 2016-2025, when Asia accounted for 36.4% of assignments and Europe increased to 26.0%, while the

proportional contribution of North America declined to 23.4%. Despite this broadening, Africa, South America and Oceania each remained below 6% during the most recent decade. Among the 206 studies with sufficiently specific geographic information, river/estuary systems were the dominant system focus, accounting for 53.4% of the evidence base (Fig. 1b). Mixed-system studies, defined as studies examining more than one estuarine system type, represented a further 30.1%, while estuarine ecosystem studies accounted for 9.2%. Groundwater-linked estuarine systems and coastal lakes/lagoons were examined less frequently, representing 5.3% and 1.9% of studies, respectively. Several estuarine systems received repeated attention. The Pearl River Estuary (China) was the most frequently studied site, followed by the Yangtze River Estuary (China) and San Francisco Estuary (USA). Chesapeake Bay, the Humber Estuary, Modaomen Estuary and Co Chien River were also prominent research locations. Overall, the geographic distribution indicates that the evidence base is concentrated within a relatively small number of intensively studied estuaries, whereas many regions and estuarine settings remain comparatively underrepresented. However, these patterns should be interpreted cautiously because the number, type and distribution of estuarine systems differ among continents; therefore, lower study representation does not necessarily indicate a proportional lack of research effort.

Methodological approaches also shifted through time (Fig. 1c). Numerical modelling became the dominant methodological approach after 2005, increasing from 20% of recorded methodology selections in 1996-2005 to 42% in 2006-2015 and remaining similarly prominent at 41% during 2016-2025 (Supplementary Data 1). Across the whole period, numerical modelling accounted for 40% of all methodology selections. Observational and field-based approaches remained relatively stable, contributing 23% overall, while conceptual and analytical approaches accounted for 21%. Experimental and laboratory approaches declined from 20% in the earliest decade to 7% in the most recent decade, representing 9% overall. Artificial intelligence and machine-learning applications remained uncommon but emerged primarily during the latest period, accounting for 4% of all methodology selections. These trends indicate a methodological transition from predominantly observational and experimental investigations towards model-based analyses, while artificial intelligence and machine-learning approaches remain an emerging component of the evidence base.


(a)
1996–2005
2006–2015
2016–2025
Cumulative Articles
Yearly International
Yearly Domestic
Yearly Articles
Cumulative Articles
Year
(b)
1996–2005
2006–2015
2016–2025
Full period 1996–2025
Asia
Europe
North America
South America
Africa
Oceania
53.4%
30.1%
9.2%
5.3%
1.9%
Studies (%)
Dominant system focus
River/estuary
Coastal lake/lagoon
Groundwater
Estuarine ecosystem
Mixed system focus
Study frequency
1 study
2 studies
3–5 studies
10–14 studies
(c)
1996–2005
2006–2015
2016–2025
1996–2025
Observational/ Field
Experimental/ Lab
Numerical modelling
Conceptual/ Analytical
AI/ML
Review/ Synthesis

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Figure 1: Temporal growth and global distribution of research.

(a) Annual and cumulative growth of saltwater intrusion research by domestic and international authorship, 1996-2025. In (a), solid dark-blue bars represent domestic studies, while hatched white bars represent international studies. The dashed green line and circular markers show the cumulative number of studies published from 1996 through each successive year. (b) Geographic distribution and dominant system focus from 206 of the 222 studies for which sufficiently specific geographic information was available, and temporal changes in continental distribution from 1996 to 2025. In (b), the main map shows the geographic distribution of study sites included in the review. Each symbol represents a study location, with symbol size scaled to the number of studies associated with that site. Symbol shape and colour identify the dominant system focus on each location. The horizontal inset bar chart summarises the relative distribution of studies among dominant system-focus categories. The radar diagram presents continental distributions based on unique study-continent assignments. Studies covering multiple continents contributed once to each relevant continent; therefore, percentages were calculated using the number of study-continent assignments within each period rather than the number of individual studies. The full-period series is shown as a dashed black line, while the three decadal series are distinguished by colour, marker shape and light transparent fills. (c) Temporal shifts of methodological approaches. In (c), donut charts show the relative distribution of all recorded methodology instances during 1996-2005, 2006-2015 and 2016-2025, and across the full study period (1996-2025). Percentages show the share of all recorded methodology selections accounted for by each methodology within each period. The unlabelled slices in 2006-2015 each represent approximately 2%.

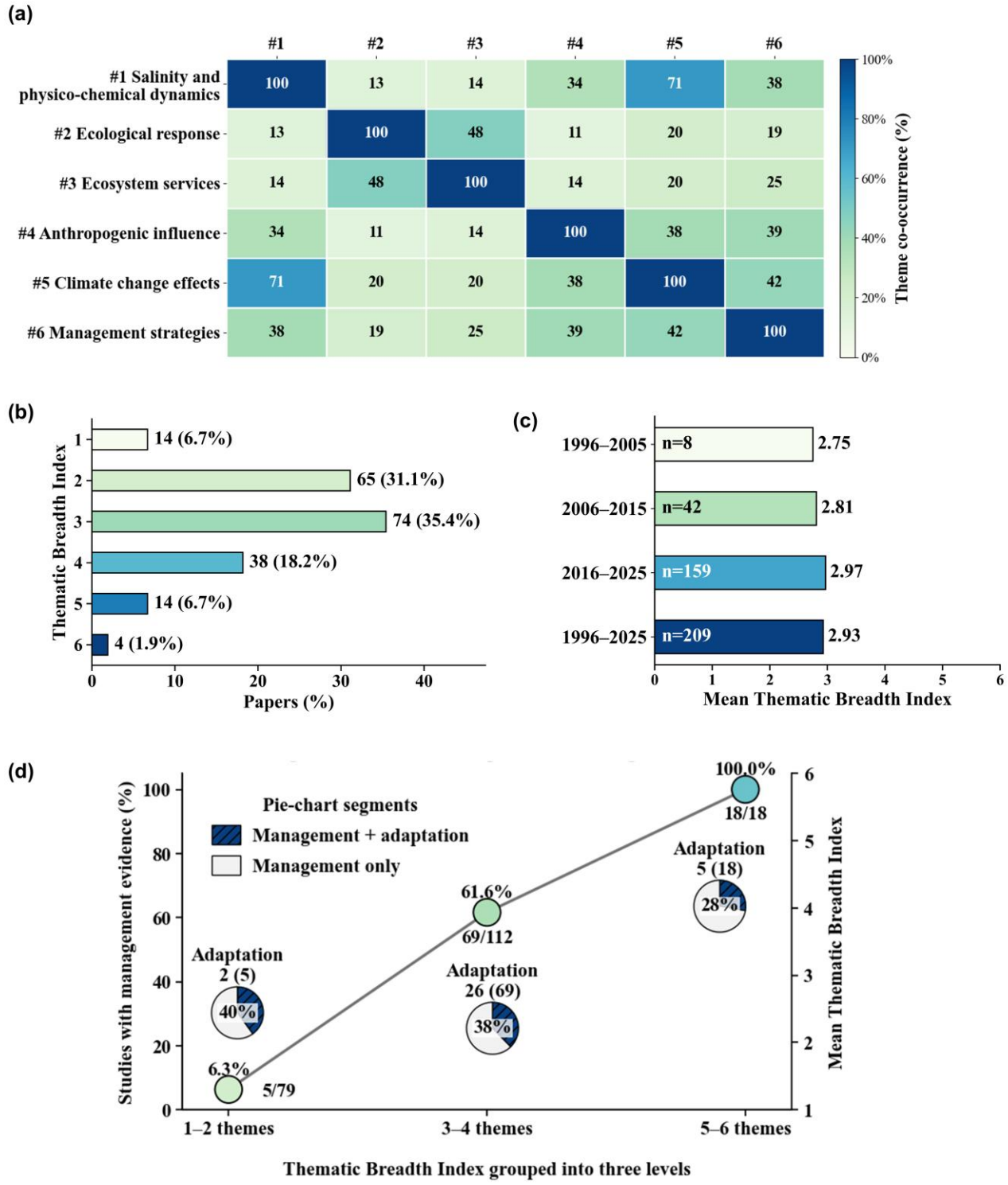
Thematic breadth and management relevance

Thematic breadth across the six coded domains (i.e., salinity and physico-chemical dynamics, ecological response, ecosystem services, anthropogenic influence, climate-change effects and management strategies) was uneven, with strong integration between some domains but limited connectivity among others (Fig. 2a). The strongest pairwise co-occurrences were between salinity and physico-chemical dynamics and climate-change effects, which occurred jointly in 71% of studies assigned to either theme. Ecological response was also frequently linked with ecosystem services, with a co-occurrence of 48%. Management evidence showed its strongest connections with climate-change effects and anthropogenic influence, with co-occurrence values of 42% and 39%, respectively. By contrast, ecological response was weakly connected with anthropogenic influence (11%) and salinity and physico-chemical dynamics (13%) (Supplementary Data 1). Ecosystem services also showed limited integration with salinity and physico-chemical dynamics and anthropogenic influence, both at 14%. Thematic integration was strongest where studies linked climatic drivers with physical processes, whereas connections between physical, ecological and management domains remained comparatively limited.

Most studies covered a moderate number of themes rather than focusing narrowly on a single domain or integrating the full thematic framework (Fig. 2b). Among the 209 studies included in the thematic analysis, 74 studies (35.4%) addressed three themes, representing the most common breadth level. A further 65 studies (31.1%) covered two themes, while 38 studies (18.2%) addressed four (Supplementary Data 1). Studies at the extremes of the distribution were uncommon: 14 studies (6.7%) examined only one theme, another 14 (6.7%) covered five themes, and only four studies (1.9%) integrated all six themes. Overall, nearly two-thirds of the evidence base addressed only two or three thematic domains, while fewer than one in ten studies covered five or six. Thematic breadth increased gradually through time, although the magnitude of change was moderate (Fig. 2c). The mean Thematic Breadth Index, defined as the number of themes addressed within each study, increased from 2.75 during 1996-2005 to 2.81 during 2006-2015 and 2.97 during 2016-2025. Across the whole 1996-2025 period, studies addressed an average of 2.93 themes (Fig. 2c; Supplementary Data 1).

Management relevance increased sharply with thematic breadth (Fig. 2d). Only 5 of 79 studies addressing one or two themes contained management evidence, equivalent to 6.3%. This proportion increased to 61.6% among studies covering three or four themes, with 69 of 112 studies discussing management evidence. All 18 studies integrating five or six themes contained management evidence. Adaptation evidence showed a similar relationship with breadth but remained less common than management evidence. Among management-focused studies, adaptation was identified in 2 of 5 studies within the

lowest breadth level, 26 of 69 studies within the intermediate level, and 5 of 18 studies within the highest level. Because management evidence constituted one of the six themes used to calculate the Thematic Breadth Index, the observed relationship could partly reflect an automatic association. To test whether broader thematic coverage outside the management domain was associated with management relevance, thematic breadth was recalculated using only the five non-management themes. The same overall pattern remained, management evidence occurred in 5 of 19 studies (26.3%) covering zero or one non-management domain, 69 of 166 studies (41.6%) covering two or three domains, and 18 of 24 studies (75.0%) covering four or five domains (Supplementary Data 1). Adaptation relevance also increased across these breadth groups, from 10.5% to 15.7% and 20.8%, respectively. These findings indicate that broader integration across knowledge domains is consistently associated with greater management relevance, although progression towards adaptation evidence remains comparatively modest.


(a)
#1
#2
#3
#4
#5
#6
#1 Salinity and physico-chemical dynamics
#2 Ecological response
#3 Ecosystem services
#4 Anthropogenic influence
#5 Climate change effects
#6 Management strategies
100 13 14 34 71 38
13 100 48 11 20 19
14 48 100 14 20 25
34 11 14 100 38 39
71 20 20 38 100 42
38 19 25 39 42 100
100%
80%
60%
40%
20%
0%
Theme co-occurrence (%)
(b)
Thematic Breadth Index
1
2
3
4
5
6
14 (6.7%)
65 (31.1%)
74 (35.4%)
38 (18.2%)
14 (6.7%)
4 (1.9%)
0
10
20
30
40
Papers (%)
(c)
1996–2005
2006–2015
2016–2025
1996–2025
n=8
n=42
n=159
n=209
2.75
2.81
2.97
2.93
0
1
2
3
4
5
6
Mean Thematic Breadth Index
(d)
Studies with management evidence (%)
0
20
40
60
80
100
Pie-chart segments
Management + adaptation
Management only
100.0%
18/18
Adaptation
5 (18)
28%
61.6%
69/112
Adaptation
26 (69)
38%
Adaptation
2 (5)
40%
6.3%
5/79
1–2 themes
3–4 themes
5–6 themes
Thematic Breadth Index grouped into three levels
Mean Thematic Breadth Index
1
2
3
4
5
6

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Figure 2: Thematic integration, breadth and management relevance of saltwater intrusion research.

(a) Pairwise co-occurrence among six thematic domains in studies published between 1996 and 2025. Each cell shows the Jaccard similarity coefficient for a pair of themes, with darker shading indicating stronger co-occurrence. (b) Distribution of studies across Thematic Breadth Index values from one to six for the period 1996–2025. Bar length indicates the percentage of studies assigned to each value. (c) Mean Thematic Breadth Index for studies published during 1996-2005, 2006-2015 and 2016-2025, and across the full 1996-2025 period. (d) Management and adaptation evidence across grouped thematic breadth levels in studies published from 1996 to 2025. Connected points show the percentage of all studies within each group that contained management evidence; fractions beside the points report the number containing management evidence relative to the total number of studies in that group. Inset pie charts show, among studies containing management evidence, the proportion that also contained adaptation evidence. Labels above the pies report the number of studies containing adaptation evidence, with the number of management-focused studies in parentheses.

Evidence bottlenecks along the risk-to-adaptation pathway

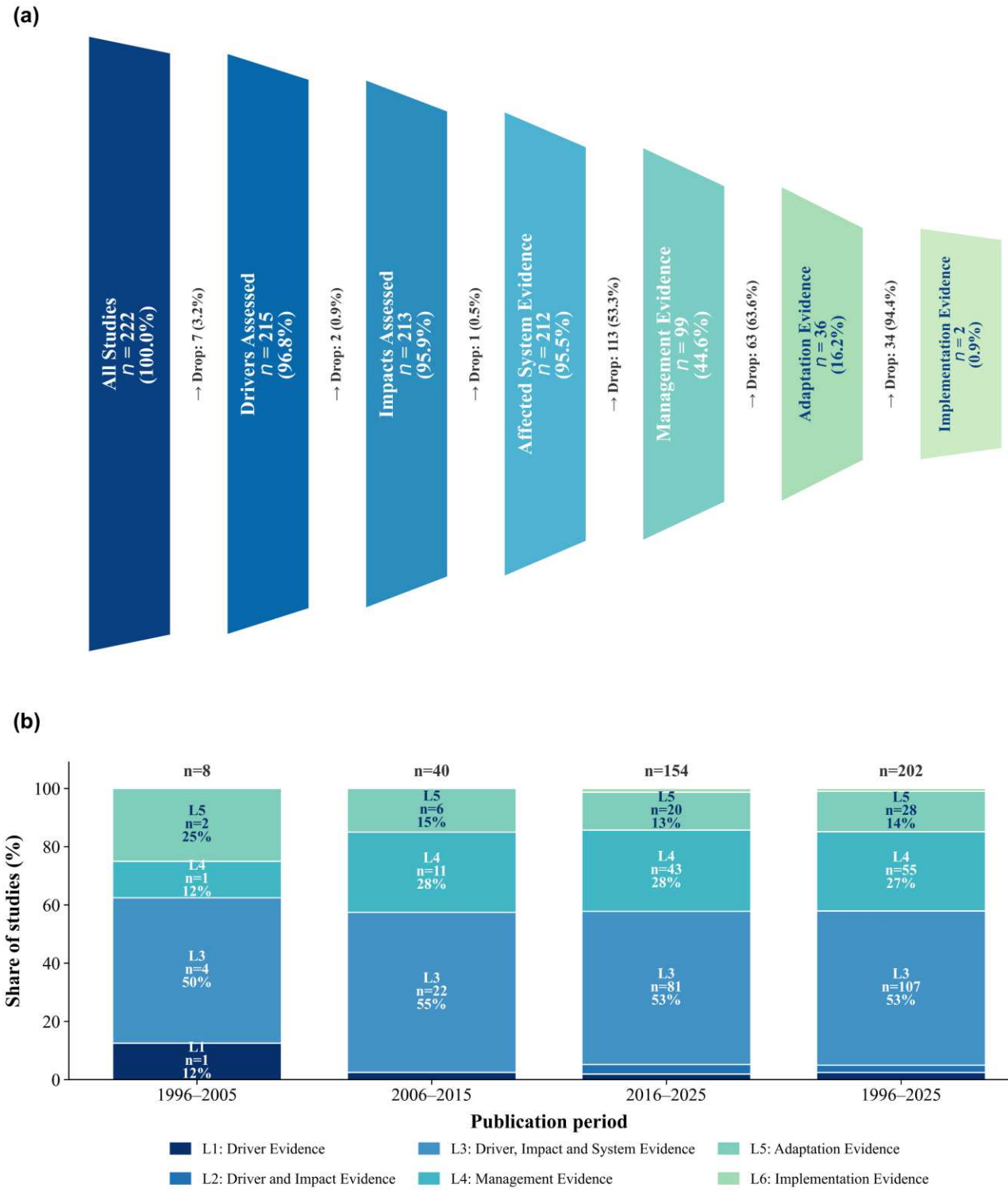
Most studies successfully characterised saltwater intrusion hazards, drivers or impacts but did not progress to evaluating management responses. Consequently, evidence, defined here as the information generated at successive stages of the risk-to-adaptation pathway, became progressively less common as studies advanced towards management and adaptation responses (Fig. 3a). Of the 222 studies, 215 (96.8%) examined at least one anthropogenic or climatic driver, while 213 (95.9%) assessed an associated impact or hazard. A similarly high proportion contained affected system evidence, with 212 studies (95.5%) connecting saltwater intrusion to an ecological, social, economic or infrastructure end user (Supplementary Data 1). The evidence base showed only small reductions across the initial stages of driver identification, impact assessment and risk translation, with reductions of seven, two and one studies between successive components, respectively. These findings indicate that the literature provides consistently substantial evidence of drivers, associated hazards and impacts, and affected systems during the early stages of the risk-to-adaptation pathway.

A much sharper decline appeared once the evidence pathway reached the management and adaptation stages. Management evidence was presented in 99 studies, representing 44.6% of the total evidence base and a reduction of 113 studies relative to those containing affected system evidence. Only 36 studies (16.2%) contained adaptation evidence, corresponding to a further reduction of 63 studies from the management stage. Evidence of implementation was exceptionally limited; only two studies (0.9%) documented an implemented adaptation response. Thus, although most studies characterised drivers, impacts and affected systems, fewer than half progressed to management, approximately one in six contained adaptation evidence, and fewer than 1 in 100 provided implementation evidence. This sharp reduction marks the principal evidence bottleneck, where research transitions from understanding climate risks towards evaluating and implementing adaptation responses.

The cumulative readiness classification assessed how far each study progressed along the sequential evidence pathway, from identifying drivers (L1), through impacts and affected systems (L2-L3), to management evidence (L4), adaptation (L5) and implementation evidence (L6) (Fig. 3b). Assignment to a level required the study to meet that level and all preceding levels. This cumulative readiness classification produced a similar pattern (Fig. 3b). Among the 202 studies meeting the entry requirements for the sequential framework (7 studies did not meet the L1 driver-entry requirement and 13 studies met L1 but were published in 2026), more than half were assigned to tier L3, indicating that they connected drivers, impacts and affected systems but did not progress further along the pathway. Across the full period, 107 studies (53%) were classified at L3, making it the dominant readiness level. A further 55

studies (27%) reached L4 by including management evidence, while 28 studies (14%) reached L5 by containing adaptation evidence (Supplementary Data 1). Only a very small proportion (1%) reached L6, demonstrating the rarity of implementation evidence. Studies terminating at L1 or L2 were also uncommon because most papers that assessed drivers additionally examined impacts and affected systems. Overall, the readiness classification confirms that most studies progress successfully through hazard characterisation but terminate before generating adaptation-ready evidence.

The distribution of readiness levels varied only moderately through time. During 1996-2005, four of eight studies (50%) were classified at L3, while one reached L4 and two reached L5. In 2006-2015, L3 remained dominant, accounting for 22 of 40 studies (55%), followed by 11 studies (28%) at L4 and six (15%) at tier L5. The evidence base expanded substantially during 2016-2025, but its proportional structure remained similar: 81 of 154 studies (53%) terminated at L3, 43 (28%) reached management evidence and 20 (13%) reached adaptation evidence (Supplementary Data 1). The rapid growth of saltwater intrusion research increased the absolute volume of management and adaptation relevant evidence but did not substantially alter the point at which most studies terminated. Across all decades, the dominant pathway remained progression through risk characterisation and system identification, followed by a persistent bottleneck before adaptation and implementation. Thus, despite three decades of rapid research growth, the overall maturity of the evidence base has changed comparatively little, with the principal transition from hazard science to adaptation remaining consistently underdeveloped.


(a)
All Studies
n = 222
(100.0%)
→ Drop: 7 (3.2%)
Drivers Assessed
n = 215
(96.8%)
→ Drop: 2 (0.9%)
Impacts Assessed
n = 213
(95.9%)
→ Drop: 1 (0.5%)
Affected System Evidence
n = 212
(95.5%)
→ Drop: 113 (53.3%)
Management Evidence
n = 99
(44.6%)
→ Drop: 63 (63.6%)
Adaptation Evidence
n = 36
(16.2%)
→ Drop: 34 (94.4%)
Implementation Evidence
n = 2
(0.9%)
(b)
n=8
n=40
n=154
n=202
Share of studies (%)
100
80
60
40
20
0
L5 n=2 25%
L4 n=1 12%
L3 n=4 50%
L1 n=1 12%
L5 n=6 15%
L4 n=11 28%
L3 n=22 55%
L5 n=20 13%
L4 n=43 28%
L3 n=81 53%
L5 n=28 14%
L4 n=55 27%
L3 n=107 53%
1996–2005
2006–2015
2016–2025
1996–2025
Publication period
L1: Driver Evidence
L2: Driver and Impact Evidence
L3: Driver, Impact and System Evidence
L4: Management Evidence
L5: Adaptation Evidence
L6: Implementation Evidence

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Figure 3: Progression and evidence bottlenecks along the risk-to-adaptation pathway.

(a) Non-cumulative evidence profile showing the progressive reduction in studies from driver and impact assessment to management, adaptation and implementation evidence. Numbers and percentages within the coloured segments indicate the number and proportion of studies addressing each component, calculated relative to the full dataset of 222 studies. Arrows indicate the absolute and percentage reduction relative to the preceding component. (b) Temporal distribution of six cumulative adaptation evidence maturity levels from 1996 to 2025. Numbers and percentages within labelled segments indicate the number and proportion of studies assigned to their highest completed maturity level within each period (Methods). Segments representing less than 7% are included in calculations but not labelled to avoid crowding. The analysis includes 202 studies; seven did not meet the L1 driver-entry requirement, and 13 studies meeting L1 were published in the incomplete year 2026 and were excluded from the temporal analysis.

Connectivity and gaps in driver-impact-adaptation pathways

The evidence network was dominated by pathways connecting climatic and hydrological drivers to freshwater salinisation and water-resource impacts, whereas substantially fewer pathways extended through management to adaptation (Fig. 4a; Supplementary Data 1). Sea-level rise, catchment hydrology and coastal processes formed the most prominent drivers of saltwater intrusion, while anthropogenic pressures were also linked to multiple impact categories. Temperature and evapotranspiration contributed a comparatively small share of the driver evidence. Among the impacts, freshwater and groundwater salinisation was by far the most frequently reported, often linked to sea-level rise, changing catchment hydrology and coastal processes. Habitats and biodiversity degradation, nutrients and chemical imbalance, and soil salinity and crop loss formed secondary pathways, whereas infrastructure damage and socio-economic impacts were less frequently represented.

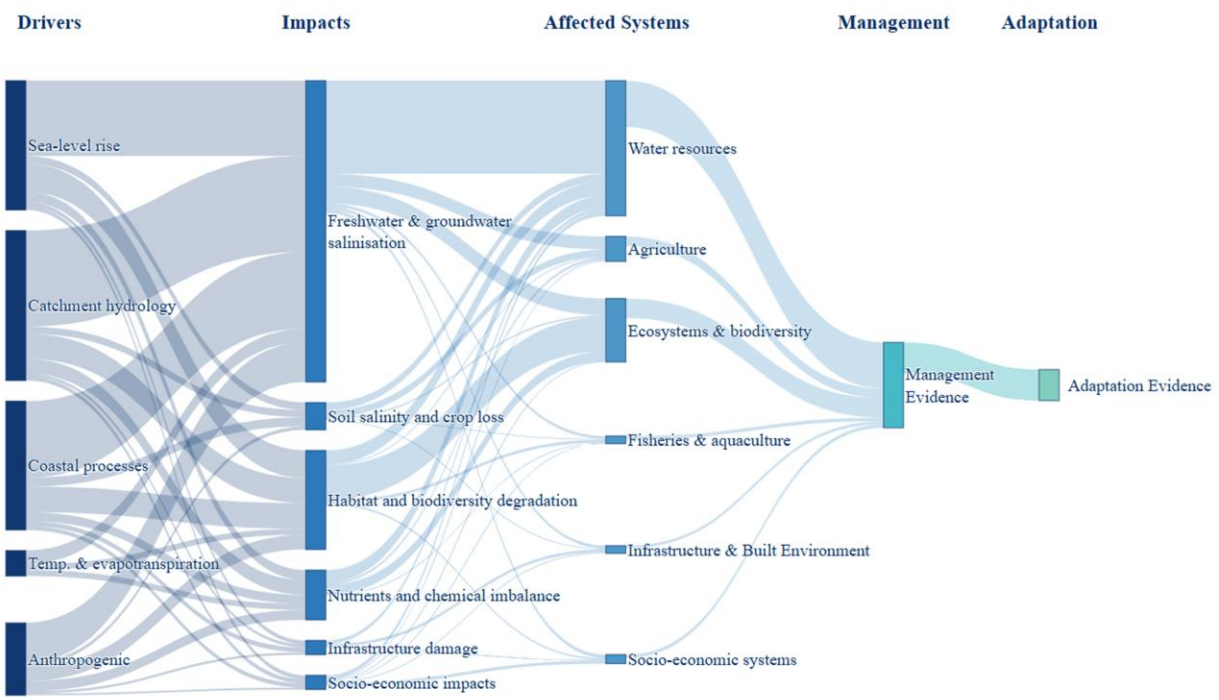
Water resources were the dominant affected systems and received evidence from nearly all impact categories (Fig. 4a). The strongest evidence pathway connected freshwater and groundwater salinisation to water resources, although nutrients and chemical imbalance, habitat degradation and socio-economic impacts were also connected to this system. Ecosystems and biodiversity formed the second major system pathway, driven primarily by habitat and biodiversity loss and, to a lesser extent, freshwater salinisation and chemical imbalance. Agriculture was most strongly associated with soil salinity and crop loss and freshwater salinisation. By comparison, fisheries and aquaculture, infrastructure and the built environment, and socio-economic systems were connected by relatively narrow evidence flows, indicating that these systems were less frequently assessed. These patterns demonstrate that the evidence base remains strongly centred on water-resource impacts, whereas other systems receive comparatively limited attention despite their recognised vulnerability to saltwater intrusion.

The impact-system matrix demonstrated that the largest evidence concentrations did not necessarily correspond to the strongest adaptation coverage (Fig. 4b; Supplementary Data 1). Freshwater and groundwater salinisation impacting water resources was the most frequently studied combination and contained the largest share of management evidence; however, only 28 studies within this combination contained adaptation evidence. Adaptation evidence for freshwater salinisation was less common in agriculture, ecosystems and biodiversity, infrastructure, and socio-economic systems, with 7, 6, 1 and 3 studies, respectively. Habitat and biodiversity degradation impacting ecosystems and biodiversity formed another prominent combination, but only 9 studies contained adaptation evidence within this pathway. Soil salinity and crop loss was linked mainly to water resources and agriculture, with 6 adaptation studies in each combination. Nutrients and chemical imbalance were associated with adaptation evidence in seven

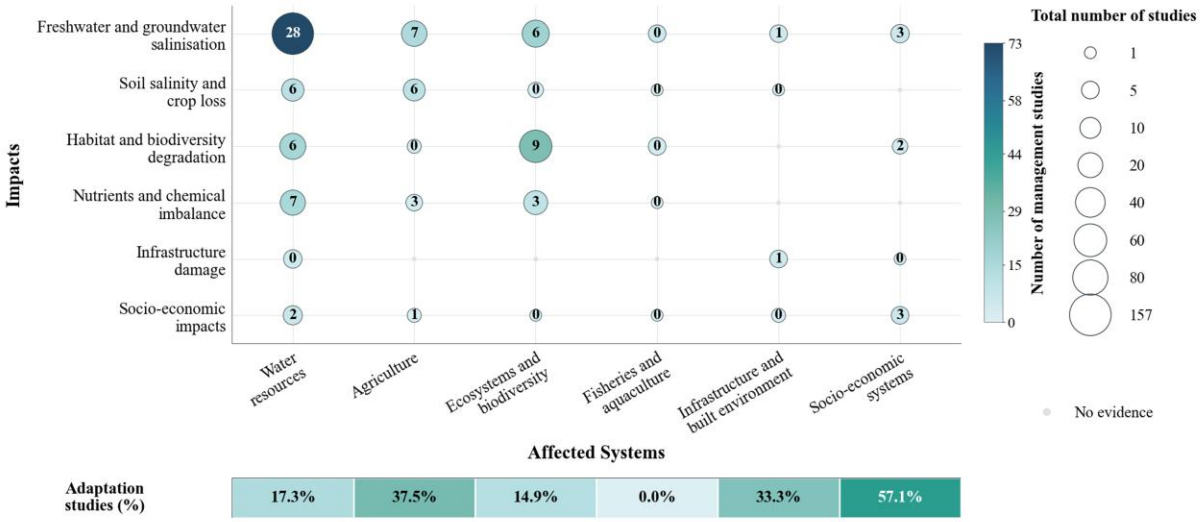
studies involving water resources, three involving agriculture and three involving ecosystems and biodiversity. Thus, even the most intensively studied impact-system pathways rarely progressed beyond management evidence to explicit assessment of adaptation responses.

Several impact-system combinations included little or no adaptation evidence. No studies containing adaptation evidence were identified for fisheries and aquaculture across any of the six impact categories, despite evidence that this system was affected by freshwater salinisation and habitat degradation. Adaptation evidence was also absent for infrastructure damage affecting water resources or socio-economic systems and for several ecological and socio-economic pathways. At the system level, the proportion of studies containing adaptation evidence was highest for socio-economic systems (57.1%), followed by agriculture (37.5%) and infrastructure and built environment (33.3%) (Fig. 4b, Supplementary Data 1). Lower proportions were found for water resources (17.3%) and ecosystems and biodiversity (14.9%), while fisheries and aquaculture had no adaptation evidence. These studies strongly characterise physical drivers, salinisation impacts and water-resource exposure, but many of the pathways affecting ecological, fisheries, infrastructure and socio-economic systems remain poorly linked to adaptation evidence. Collectively, these findings indicate that research has been highly effective at identifying physical drivers, salinisation impacts and exposed systems, yet many pathways affecting ecological, fisheries, infrastructure and socio-economic systems remain weakly connected to adaptation.

(a)


Drivers
Impacts
Affected Systems
Management
Adaptation
Sea-level rise
Catchment hydrology
Coastal processes
Temp. & evapotranspiration
Anthropogenic
Freshwater & groundwater salinisation
Soil salinity and crop loss
Habitat and biodiversity degradation
Nutrients and chemical imbalance
Infrastructure damage
Socio-economic impacts
Water resources
Agriculture
Ecosystems & biodiversity
Fisheries & aquaculture
Infrastructure & Built Environment
Socio-economic systems
Management Evidence
Adaptation Evidence

(b)


Impacts
Freshwater and groundwater salinisation
Soil salinity and crop loss
Habitat and biodiversity degradation
Nutrients and chemical imbalance
Infrastructure damage
Socio-economic impacts
28 7 6 0 1 3
6 6 0 0 0
6 0 9 0 2
7 3 3 0
0 1 0
2 1 0 0 0 3
Water resources
Agriculture
Ecosystems and biodiversity
Fisheries and aquaculture
Infrastructure and built environment
Socio-economic systems
Affected Systems
Adaptation studies (%)
17.3%
37.5%
14.9%
0.0%
33.3%
57.1%
Total number of studies
Number of management studies
73
58
44
29
15
0
1
5
10
20
40
60
80
157
No evidence

379

Figure 4: Connectivity and evidence gaps across driver-impact-adaptation pathways across the complete dataset of 222 studies.

(a) Sankey diagram linking drivers, impacts, affected systems, management evidence and adaptation evidence. Link widths represent the number of studies in which connected categories co-occurred and should not be interpreted as causal relationships or evidence of adaptation effectiveness. (b) Distribution of evidence across impact-system combinations. Bubble size represents the total number of studies addressing each combination, bubble colour indicates the number containing management evidence, and values within bubbles indicate the number containing adaptation evidence. Grey points identify combinations for which no evidence was recorded; absence of evidence should not be interpreted as evidence of no relationship. The segmented strip shows the proportion of studies within each affected system containing adaptation evidence.

Discussion

From hazard knowledge to adaptation-ready evidence

Saltwater intrusion research in estuarine environments has expanded rapidly over the past three decades, particularly since the late 2010s, accompanied by major advances in field observations[43], long-term monitoring[44], numerical modelling[45], scenario analysis and climate-impact assessment[46]. Together, these approaches have substantially improved understanding of how sea-level rise, altered freshwater inflows, tides, extreme events and anthropogenic pressures influence the magnitude, timing and upstream extent of saltwater intrusion[47–49]. Our synthesis demonstrates that the literature is mature in characterising climate drivers, impacts and affected systems, with almost all of the reviewed studies progressing through these initial stages of the risk pathway. However, this progression declines sharply once research moves beyond understanding risk towards evaluating responses. Although almost half of the reviewed studies discussed management implications, only a small proportion contained adaptation evidence and implementation evidence was exceptionally rare. Therefore, within the better-studied themes and systems represented in the reviewed literature, the principal constraint is not hazard characterisation itself but translating existing hazard knowledge into evidence that can inform adaptation decisions. However, for less-studied themes and estuarine systems, even the causes, extent and severity of saltwater intrusion may not yet be adequately understood.

Understanding how saltwater intrusion may change is an essential first step in adaptation planning. However, the evidence base now needs to extend beyond hazard characterisation to identify which responses are appropriate, the conditions under which they should be implemented, and whether they will remain effective under changing climatic and socio-environmental conditions[26,50,51]. Increasingly sophisticated hazard assessments cannot, on their own, determine intervention thresholds, evaluate feasibility, quantify trade-offs or demonstrate implementation success. Adaptation-ready evidence therefore requires additional forms of knowledge that extend beyond physical process understanding.

The limited implementation evidence identified in this review should also be interpreted cautiously. Progression to the response phase is often driven by governments, relevant agencies, industry bodies and local communities responsible for planning and implementation. Consequently, many implemented responses are likely documented within government reports, technical guidance and programme evaluations rather than the English-language peer-reviewed literature examined here. Nevertheless, the persistence of the evidence bottleneck over three decades suggests that publication growth alone is unlikely to close the gap between understanding climate risk and supporting climate-resilient decisions.

Future progress will depend not on replacing hazard science, but on strengthening collaboration between researchers, governments and relevant agencies to design hazard assessments that explicitly connect projected change with decision thresholds, intervention pathways, implementation and long-term monitoring and learning.

Uneven integration constrains adaptation pathways

The positive relationship between thematic breadth and management relevance suggests that integration across knowledge domains can help move research from hazard characterisation towards adaptation. Studies addressing a broader range of physical, ecological, anthropogenic and management themes were substantially more likely to contain management evidence, while adaptation relevance also increased with thematic breadth, albeit more modestly. Evaluating adaptation requires connecting climatic hazards and physical processes with affected systems, intervention points and the practical conditions shaping decision-making. Adaptation readiness therefore depends not simply on the quantity of evidence, but on how effectively different forms of knowledge are connected to support decisions[26,52].

The strongest integration occurred between climate-change effects, salinity and physico-chemical dynamics, reflecting the emphasis on understanding how sea-level rise, altered freshwater inflows and coastal processes influence estuarine salinity. Connections with ecological responses, ecosystem services and anthropogenic pressures were considerably weaker. These discontinuities matter because adaptation requires more than quantifying salinity change; it requires evidence linking physical change to ecological function, infrastructure, livelihoods and other valued outcomes, while identifying where interventions may reduce those consequences[53]. The principal limitation is therefore not an absence of recognised impacts, but their comparatively weak translation into system-specific adaptation evidence.

The integrated pathway analysis similarly showed that evidence is concentrated around freshwater and groundwater salinisation and water resources. These pathways are comparatively mature because they involve measurable thresholds and operational decisions, including drinking-water abstraction, irrigation suitability and reservoir operation, which can directly connect hazard information with management responses[54]. Their relative maturity may also reflect how research is organised. Freshwater availability, irrigation and reservoir operations are commonly studied within hydrology and water-resources disciplines, whereas saltwater intrusion and sea-level rise are often approached through coastal science

and engineering. Such disciplinary separation can limit understanding of how coastal hazards propagate through connected freshwater, ecological and socio-economic systems.

This fragmentation is also relevant to food-energy-water (FEW) nexus research, which seeks to understand interdependencies and trade-offs across sectors. Saltwater intrusion appears to remain underrepresented in major FEW syntheses[55–57], despite its potential to affect irrigation, agricultural productivity, aquaculture, freshwater supply and reservoir operations. This matters particularly in estuaries and deltas, where coastal and inland water systems are tightly connected and salinity changes can generate cascading effects across sectors.

Future research should therefore strengthen poorly connected pathways involving biodiversity, fisheries and aquaculture, infrastructure and socio-economic systems by integrating coastal and catchment processes with impacts, affected systems and adaptation responses. This requires closer connections among coastal science, hydrology, ecology, water-resources and nexus research, while explicitly evaluating trade-offs, transferred risks and maladaptation[58]. Such integration would better reflect estuaries as connected coastal-freshwater-ecological-social systems and help convert hazard knowledge into adaptation-ready evidence.

Translating hazard knowledge into adaptation actions

This review identified a broad portfolio of adaptation responses rather than an absence of adaptation options. Structural and operational measures, nature-based solutions, flow regulation, aquifer and alternative water-supply management, land-use and livelihood adaptation, monitoring and decision-support systems, and governance and enabling measures have all been proposed to reduce saltwater intrusion risks. These responses intervene through different mechanisms, including modifying the hazard itself, reducing exposure or vulnerability, strengthening ecosystem resilience, and enhancing adaptive capacity (Fig. 5a). Collectively, they demonstrate that estuarine adaptation requires a diverse portfolio of complementary responses rather than reliance on any single intervention. However, the availability of adaptation options should not be confused with the availability of evidence needed to support their application. Identifying a potential response is only the starting point; adaptation decisions require evidence that demonstrates when, where and under what conditions that response is likely to be effective.

Fig. 5b conceptualises the progression from adaptation options to adaptation-ready evidence. This progression extends beyond response identification to defining the management objective and intervention

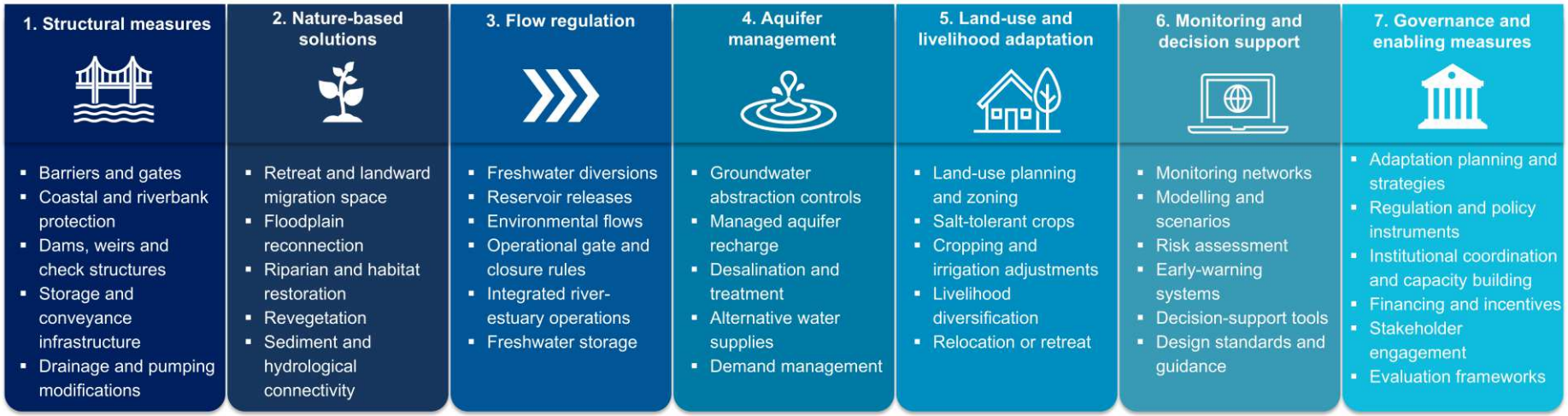
mechanism, evaluating effectiveness, assessing technical, economic and institutional feasibility, considering trade-offs and distributional consequences, implementing interventions, and monitoring outcomes to support learning and adjustment. Rather than representing a strictly linear sequence, these stages form an iterative process in which monitoring, evaluation and new knowledge continually inform whether responses should be refined, combined or replaced as environmental and societal conditions change. Adaptation-ready evidence therefore represents substantially more than evidence that an option exists; it provides the information needed to support robust, transparent and adaptive decision-making.

Across all intervention types, appraisal should extend beyond technical performance to consider effectiveness under present and future climate conditions, economic feasibility, governance capacity, social acceptability and equity, ecological consequences, uncertainty, reversibility, and cross-system trade-offs. Residual risk, co-benefits and maladaptation should also be evaluated explicitly, because measures that reduce salinity impacts in one location or system may transfer risks elsewhere, constrain future adaptation pathways or create unintended ecological consequences[26,53,58]. Evidence from implemented estuarine interventions illustrates why monitoring and adaptive learning are integral to adaptation-ready evidence. For instance, controlled seawater reintroduction for ecological restoration revealed salt accumulation and transport risks that required responsive floodgate operation to protect freshwater intakes[59], whereas managed dike realignment for flood accommodation and saltmarsh development revealed trade-offs associated with soil salinisation and reduced agricultural suitability[60]. Neither intervention was designed specifically to control saltwater intrusion; instead, both demonstrate how broader adaptation actions can alter salinity dynamics and generate outcomes ranging from risk reduction and co-benefits to cross-sector trade-offs, risk redistribution and potential maladaptation. These examples show that intervention performance cannot be judged solely against its intended objective and reinforce the need for baseline assessment, multidimensional evaluation criteria and long-term monitoring to identify unintended consequences and support timely adjustment. This broader perspective shifts adaptation assessment from asking whether a response can reduce risk to evaluating whether it remains effective, equitable and sustainable over time.

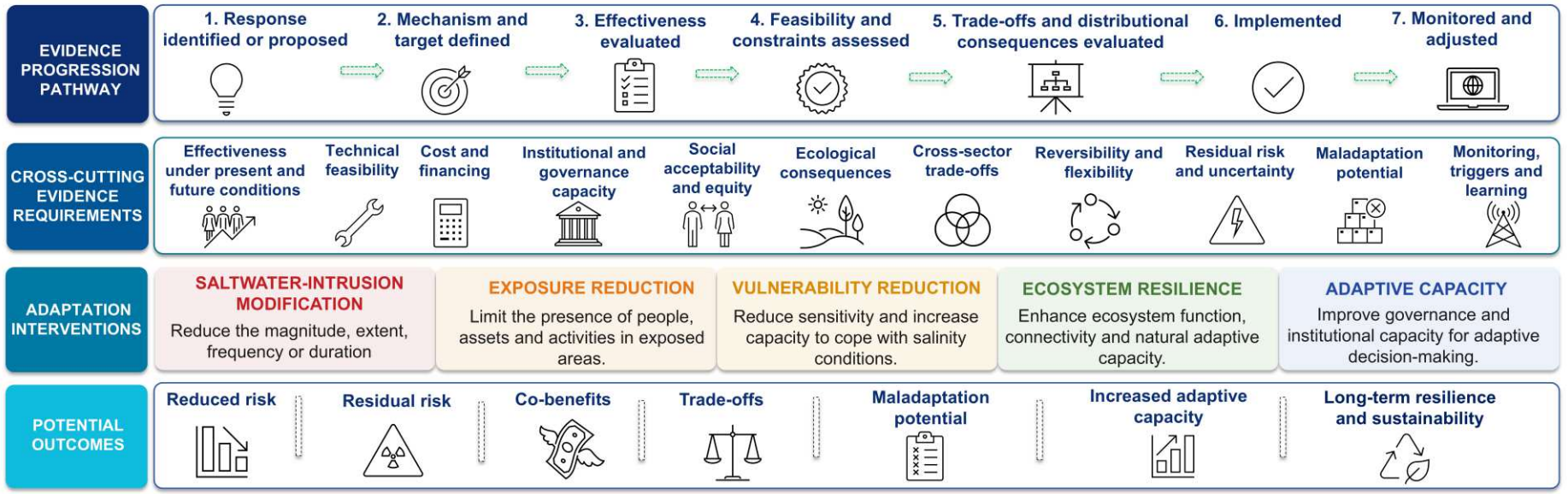
Ultimately, the future challenge is no longer simply understanding how saltwater intrusion will change, but generating the evidence needed to determine when, where and under what conditions adaptation responses should be implemented, evaluated and adjusted. Fig. 5 synthesises this progression from adaptation options to adaptation-ready evidence, providing a practical framework for strengthening future research, improving the translation of hazard science into decision-relevant knowledge, and supporting more climate-resilient estuarine management. Although developed within the context of saltwater

intrusion, the framework may also provide a useful lens for examining evidence maturity in other climate-risk domains where similar evidence-to-action gaps persist.

(a)


1. Structural measures
Barriers and gates
Coastal and riverbank protection
Dams, weirs and check structures
Storage and conveyance infrastructure
Drainage and pumping modifications
2. Nature-based solutions
Retreat and landward migration space
Floodplain reconnection
Riparian and habitat restoration
Revegetation
Sediment and hydrological connectivity
3. Flow regulation
Freshwater diversions
Reservoir releases
Environmental flows
Operational gate and closure rules
Integrated river-estuary operations
Freshwater storage
4. Aquifer management
Groundwater abstraction controls
Managed aquifer recharge
Desalination and treatment
Alternative water supplies
Demand management
5. Land-use and livelihood adaptation
Land-use planning and zoning
Salt-tolerant crops
Cropping and irrigation adjustments
Livelihood diversification
Relocation or retreat
6. Monitoring and decision support
Monitoring networks
Modelling and scenarios
Risk assessment
Early-warning systems
Decision-support tools
Design standards and guidance
7. Governance and enabling measures
Adaptation planning and strategies
Regulation and policy instruments
Institutional coordination and capacity building
Financing and incentives
Stakeholder engagement
Evaluation frameworks

(b)


EVIDENCE PROGRESSION PATHWAY
1. Response identified or proposed
2. Mechanism and target defined
3. Effectiveness evaluated
4. Feasibility and constraints assessed
5. Trade-offs and distributional consequences evaluated
6. Implemented
7. Monitored and adjusted
CROSS-CUTTING EVIDENCE REQUIREMENTS
Effectiveness under present and future conditions
Technical feasibility
Cost and financing
Institutional and governance capacity
Social acceptability and equity
Ecological consequences
Cross-sector trade-offs
Reversibility and flexibility
Residual risk and uncertainty
Maladaptation potential
Monitoring, triggers and learning
ADAPTATION INTERVENTIONS
SALTWATER-INTRUSION MODIFICATION
Reduce the magnitude, extent, frequency or duration
EXPOSURE REDUCTION
Limit the presence of people, assets and activities in exposed areas.
VULNERABILITY REDUCTION
Reduce sensitivity and increase capacity to cope with salinity conditions.
ECOSYSTEM RESILIENCE
Enhance ecosystem function, connectivity and natural adaptive capacity.
ADAPTIVE CAPACITY
Improve governance and institutional capacity for adaptive decision-making.
POTENTIAL OUTCOMES
Reduced risk
Residual risk
Co-benefits
Trade-offs
Maladaptation potential
Increased adaptive capacity
Long-term resilience and sustainability

515

Figure 5: From adaptation options to adaptation-ready evidence for managing saltwater intrusion in estuaries.

(a) Conceptual synthesis of the adaptation responses identified in the reviewed literature, organised into seven broad response families: structural measures, nature-based solutions, flow regulation, aquifer and water-supply management, land-use and livelihood adaptation, monitoring and decision support, and governance and enabling measures. The categories are neither hierarchical nor mutually exclusive, and individual responses may operate through multiple intervention domains. (b) Conceptual framework showing how the adaptation responses synthesised in (a) enter the evidence-progression pathway required to establish adaptation-ready evidence and contribute to potential adaptation outcomes. The progression involves defining each response's mechanism and target, evaluating its effectiveness and feasibility, assessing trade-offs and distributional consequences, and proceeding through implementation, monitoring and adjustment. Potential outcomes encompass both intended benefits and residual or unintended consequences against which adaptation performance should be evaluated. Cross-cutting appraisal should consider performance under present and future conditions, technical and financial feasibility, governance capacity, social acceptability and equity, ecological consequences, reversibility, residual risk and maladaptation potential. The pathway is iterative rather than strictly linear, with monitoring and learning informing the modification, combination or replacement of responses.

Methods

Review design and protocol

This study used a systematic evidence-review and mapping approach to synthesise the global literature on saltwater intrusion in estuarine systems. The review aimed to characterise the distribution and characteristics of the evidence base, identify the climatic and anthropogenic drivers associated with saltwater intrusion, synthesise its reported environmental and socio-economic consequences across affected systems, and evaluate how far the literature has progressed from hazard characterisation towards management, adaptation and implementation.

The review was designed in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses 2020 statement[61]. A structured review protocol was developed before formal screening and iteratively refined during screening, data extraction, and coding. The protocol specified the review objective, database search strategy, eligibility criteria, record-management procedures, screening stages, unit of analysis, extraction variables, coding definitions, and planned synthesis methods. It also established decision rules for differentiating primary studies from review-only papers and for coding research themes, drivers, impacts, affected systems, management evidence, adaptation options, and implementation evidence.

The study combined the characteristics of a systematic review, systematic evidence map, and structured narrative synthesis. Evidence was synthesised using descriptive statistics, binary and categorical coding, thematic breadth assessment, knowledge co-occurrence analysis, temporal comparisons, evidence-pathway mapping and an adaptation evidence maturity framework.

Search strategy

A comprehensive literature search was conducted in the Web of Science Core Collection and Scopus on 14 April 2026. The search was limited to peer-reviewed research articles and review papers published in English between 1996 and 2026. Conference papers, book chapters, editorials, notes, theses, reports, and other grey literature were not included. The database search returned 824 records, comprising 339 records from Web of Science and 485 from Scopus (Fig. 6).

For consistency across analyses, temporal analyses were restricted to the 209 studies published during the three complete decades from 1996 to 2025. Accordingly, the publication-trend and methodological analyses in Fig. 1 were based on 209 studies published during 1996-2025. The geographic map and

system-focus included 206 studies with reported locations. For the 1996-2025 continental analysis, 194 studies with geographic information produced 202 unique study-continent assignments, which formed the basis for calculating continental percentages. Continental distributions were calculated at the study level rather than the site level: each study was counted once for every continent in which it included at least one study site, regardless of the number of sites within that continent. Thus, a study with multiple sites in one continent contributed one study-continent assignment, whereas a study with sites in more than one continent was counted once in each of those continents. All thematic analyses in Fig. 2, including the theme co-occurrence matrix, Thematic Breadth Index, temporal variation in thematic breadth, and management and adaptation evidence across integration levels, were restricted to the 209 studies published between 1996 and 2025. Figure 3a used the complete dataset of 222 studies. Figure 3b included 202 studies published between 1996 and 2025, after excluding 7 studies that did not meet the L1 driver-entry criterion. The cumulative framework progresses from identifying drivers (L1), impacts (L2) and affected systems (L3) to examining management implications (L4), adaptation responses (L5) and their implementation (L6). To reach a given level, a study had to satisfy all preceding criteria. Each study was counted only once, at the highest level reached. Therefore, the stacked bars show the proportion of studies that progressed to and stopped at each readiness level, rather than the proportion containing each individual type of evidence (Figure 3b). Both the Sankey analysis (Fig. 4a) and the impact-system matrix (Fig. 4b) used the complete dataset of 222 studies. Figures 1a, 1c, and 2-4 were prepared using the data in Supplementary Data 1; Figure 1b used the site-level data in Supplementary Data 2. Variable definitions and coding criteria are provided in Supplementary Data 3.

The search strategy combined three concept groups: (i) saltwater or salinity intrusion, (ii) climate change or sea-level rise, and (iii) eligible estuarine systems. Candidate terms were derived from established saltwater intrusion and estuarine literature and iteratively refined to maximise search sensitivity while maintaining relevance. The search was conducted in the Web of Science Core Collection using Title (TI), Abstract (AB) and Author Keywords (AK) fields and replicated in Scopus using the TITLE-ABS-KEY field to ensure consistency across databases. The string sets for estuaries[24,62,63], climate change and sea-level rise[24,64–66], and saltwater intrusion[24,65–70] were compiled from previous literature and refined during protocol development. The conceptual structure and publication restrictions were kept consistent between databases, although the syntax was adapted to the requirements of each platform.

The complete search strings were as follows.

Web of Science: (((TI=(("salin* intru*" OR "salt* intru*" OR "seawater* intru*" OR "marine* intru*" OR "brackish* intru*" OR "salin* encroach*" OR "salt* encroach*" OR "seawater* encroach*" OR "marine*

encroach*" OR "brackish* encroach*" OR "salin* penetrat*" OR "salt* penetrat*" OR "seawater* penetrat*" OR "marine* penetrat*" OR "brackish* penetrat*" OR "salin* ingress*" OR "salt* ingress*" OR "seawater* ingress*" OR "marine* ingress*" OR "brackish* ingress*" OR "sal* wedge*") AND ("sea level* rise" OR "sea-level* rise" OR "rising* sea level*" OR "rising* sea-level*" OR "climat* chang*" OR "chang* climat*" OR "global warm*") AND ("estuar*" OR "tid* river*" OR "river*-estuar*" OR "lagoon*" OR "lake*"))) OR AB=(("salin* intru*" OR "salt* intru*" OR "seawater* intru*" OR "marine* intru*" OR "brackish* intru*" OR "salin* encroach*" OR "salt* encroach*" OR "seawater* encroach*" OR "marine* encroach*" OR "brackish* encroach*" OR "salin* penetrat*" OR "salt* penetrat*" OR "seawater* penetrat*" OR "marine* penetrat*" OR "brackish* penetrat*" OR "salin* ingress*" OR "salt* ingress*" OR "seawater* ingress*" OR "marine* ingress*" OR "brackish* ingress*" OR "sal* wedge*") AND ("sea level* rise" OR "sea-level* rise" OR "rising* sea level*" OR "rising* sea-level*" OR "climat* chang*" OR "chang* climat*" OR "global warm*") AND ("estuar*" OR "tid* river*" OR "river*-estuar*" OR "lagoon*" OR "lake*"))) OR AK=(("salin* intru*" OR "salt* intru*" OR "seawater* intru*" OR "marine* intru*" OR "brackish* intru*" OR "salin* encroach*" OR "salt* encroach*" OR "seawater* encroach*" OR "marine* encroach*" OR "brackish* encroach*" OR "salin* penetrat*" OR "salt* penetrat*" OR "seawater* penetrat*" OR "marine* penetrat*" OR "brackish* penetrat*" OR "salin* ingress*" OR "salt* ingress*" OR "seawater* ingress*" OR "marine* ingress*" OR "brackish* ingress*" OR "sal* wedge*") AND ("sea level* rise" OR "sea-level* rise" OR "rising* sea level*" OR "rising* sea-level*" OR "climat* chang*" OR "chang* climat*" OR "global warm*") AND ("estuar*" OR "tid* river*" OR "river*-estuar*" OR "lagoon*" OR "lake*"))) AND PY=(1996-2026)

SCOPUS: TITLE-ABS-KEY((("salin* intru*" OR "salt* intru*" OR "seawater* intru*" OR "marine* intru*" OR "brackish* intru*" OR "salin* encroach*" OR "salt* encroach*" OR "seawater* encroach*" OR "marine* encroach*" OR "brackish* encroach*" OR "salin* penetrat*" OR "salt* penetrat*" OR "seawater* penetrat*" OR "marine* penetrat*" OR "brackish* penetrat*" OR "salin* ingress*" OR "salt* ingress*" OR "seawater* ingress*" OR "marine* ingress*" OR "brackish* ingress*" OR "sal* wedge*") AND ("sea level* rise" OR "sea-level* rise" OR "rising* sea level*" OR "rising* sea-level*" OR "climat* chang*" OR "chang* climat*" OR "global warm*") AND ("estuar*" OR "tid* river*" OR "river*-estuar*" OR "lagoon*" OR "lake*"))) AND PUBYEAR > 1995 AND PUBYEAR < 2027 AND (LIMIT-TO (DOCTYPE,"ar") OR LIMIT-TO (DOCTYPE,"re")) AND (LIMIT-TO (LANGUAGE,"English"))

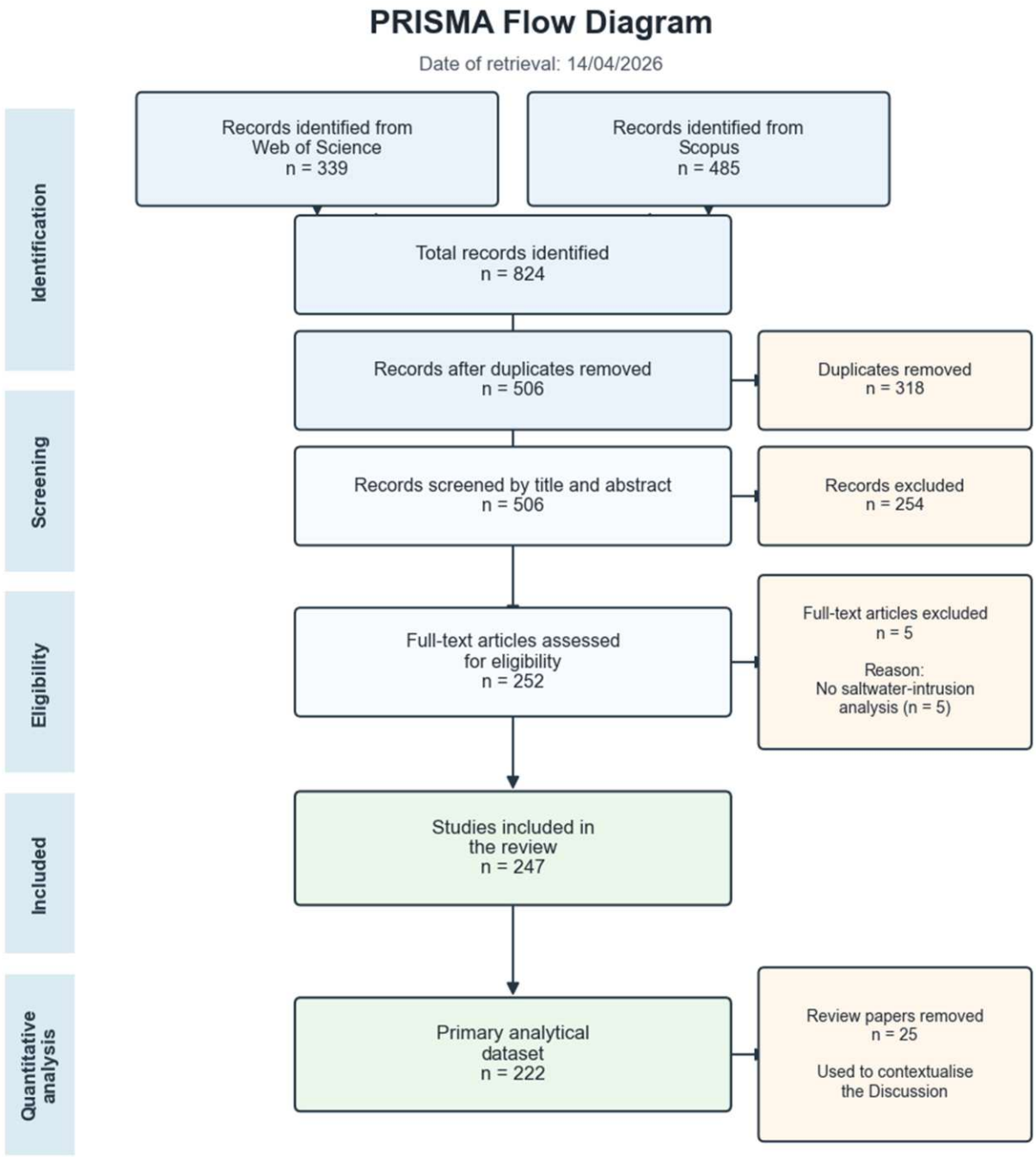


Figure 6: **PRISMA 2020 flow diagram summarising the systematic literature search and study-selection process.**

The diagram summarises the number of records identified through database searching, screened, assessed for eligibility and included in the final evidence synthesis following application of the predefined inclusion and exclusion criteria.

Eligibility criteria

The review included peer-reviewed studies that examined saltwater intrusion in estuaries, tidal rivers, coastal lakes and lagoons, deltaic and estuarine wetlands, bays or harbours influenced by river-estuary processes, and groundwater systems with a demonstrated hydrological connection to an estuarine or coastal surface-water system. For this review, saltwater intrusion was broadly defined as the upstream, landward, vertical, or lateral movement of saline water within otherwise fresher parts of an estuarine or connected coastal system. The definition included related processes described as salinity intrusion, seawater intrusion, marine intrusion, saline encroachment, saltwater ingress, salt-wedge migration, or changes in the magnitude, spatial extent, duration or frequency of salinity intrusion. Studies were eligible only when they met at least one of the following criteria: they explicitly examined saltwater, seawater, marine, or saline intrusion; evaluated movement or change in the position of a salt front, salt wedge, or defined salinity limit; investigated the upstream, landward, lateral, or vertical migration of saline water; analysed changes in the spatial extent, duration, frequency, or intensity of salinity attributable to marine-water incursion; or assessed management or adaptation measures specifically intended to address such intrusion (Table 1). Studies investigating salinity change without explicitly examining saltwater intrusion or a hydrologically connected marine source were excluded to ensure that the review remained focused on intrusion processes rather than broader estuarine salinity dynamics.

Review papers were retained during the systematic-review stage because they contributed to mapping the evolution of research themes, terminology, conceptual development, and synthesis activity within the field. However, papers based entirely on the synthesis of previous studies, without original field observations, experiments, numerical modelling, statistical analysis, or machine-learning analysis, were classified as review-only studies. These papers were excluded from analyses intended to represent primary quantitative or empirical evidence. Conversely, review papers that incorporated original analyses were retained within the primary analytical dataset.

Table 1: Inclusion criteria for selecting studies on estuarine salinity and saltwater intrusion

Criterion	Include when	Exclude when
System	Estuary or hydrologically connected coastal system	Isolated coastal, inland, offshore, or freshwater system
Process	Landward, upstream, lateral, or vertical movement of saline water	General salinity variability without saltwater intrusion
Climate context	Climate change, sea-level rise, or climate-driven hydrological change is assessed	Climate change is mentioned only in passing
Impacts	Salinity-related ecological, sectoral, or socio-economic effects are assessed	Impacts are not linked to salinity
Anthropogenic drivers	Human activities affecting saltwater intrusion are assessed	Human impacts unrelated to salinity change
Evidence type	Primary empirical, modelling, experimental, or analytical evidence	Editorials, commentaries, or abstract-only papers
Temporal scope	Contemporary or future processes	Palaeoenvironmental studies only

Record management and study selection

All records retrieved from Web of Science and Scopus were exported with their available bibliographic information and combined in a single reference library. Duplicate records were removed through a sequential process using EndNote, Rayyan, and manual verification. EndNote's duplicate-detection function was first applied using combinations of title, author names, publication year, journal, and digital object identifier. The merged library was then imported into Rayyan for an additional duplicate check. Records with incomplete or slightly different metadata were manually compared to identify duplicates not detected automatically. This process removed 318 duplicate records, leaving 506 unique records for screening. Screening consistency was supported through predefined eligibility criteria and independent assessment by three reviewers, each evaluating approximately one-third of the records.

Study selection was conducted in two stages. First, the titles and abstracts of all unique records were screened against the predefined eligibility criteria. Records were excluded at this stage when they clearly

examined systems outside the review scope, did not address saltwater intrusion or relevant salinity change, or lacked a climate change or sea-level-rise connection required by the search scope. Records were retained for full-text assessment whenever their eligibility could not be determined confidently from the title and abstract alone.

Following title and abstract screening, 252 articles were retained for full-text assessment. All full texts were initially assessed by one reviewer. Articles considered uncertain, borderline or difficult to classify were independently evaluated by two additional reviewers. This process was used to refine the interpretation of the eligibility criteria, particularly for groundwater studies, studies examining general estuarine salinity, and papers mentioning management or adaptation without substantively assessing either. Any differences in interpretation were resolved through discussion and reference to the predefined eligibility protocol before applying the agreed criteria consistently across the remaining records.

Following full-text assessment, five articles were excluded because they did not satisfy the eligibility criteria. Reasons for exclusion are summarised in the PRISMA flow diagram (Fig. 6) and included the absence of substantive saltwater intrusion analysis or relevant primary analytical evidence. This resulted in 247 studies being retained within the systematic-review database. A further 25 review-only studies were excluded from the primary analytical dataset because they contained no original empirical or analytical evidence, leaving a final analytical dataset of 222 studies. Review-only papers were retained to provide contextual background and support interpretation in the Discussion.

Data extraction and coding

The individual study was used as the unit of analysis. A structured codebook was developed and refined during extraction to define each variable and guide consistent coding (Supplementary Data 3). Most variables were coded using a binary presence-absence system, allowing multiple categories to be assigned to an individual study where appropriate. Coding involved interpretive judgement and was undertaken consistently using the predefined decision rules in Supplementary Data 3. The analysis was intended to characterise broad patterns and evidence progression across the literature.

Extracted bibliographic variables included title, authors, journal, DOI, publication year, and authorship type. Authorship was classified as domestic when all affiliations were from one country and international when affiliations spanned two or more countries. Spatial variables included country, continent, study site, estuary, coordinates, and system focus. Site names were standardised before analysis by harmonising

spelling variants, alternative names and synonymous references to the same geographic location under a common Site Key. Study methods were coded as observational or field-based, experimental or laboratory, numerical modelling/scenario-based or projection, conceptual/analytical or theoretical, artificial intelligence or machine learning, and review or synthesis. Each study was coded against six thematic domains: Salinity and Physico-Chemical Dynamics, Ecological Response, Ecosystem Services, Anthropogenic Influence, Climate Change Effects, and Management Strategies. A theme was recorded only when it formed a substantive part of the study rather than being mentioned only in the background.

Drivers were grouped as climatic or anthropogenic and coded when they were explicitly measured, tested, modelled, or analysed in relation to saltwater intrusion. Impacts included freshwater and groundwater salinisation, soil salinity and crop loss, habitat and biodiversity degradation, nutrients and chemical imbalance, infrastructure damage, and socio-economic impacts. Affected systems were coded only when the authors directly assessed, measured, modelled, or quantified the effect. Management and adaptation were coded separately. Management evidence comprised substantive strategies, interventions or actions intended to control saltwater intrusion or reduce its impacts. Adaptation evidence was recorded only when a study explicitly proposed, evaluated, compared, implemented or monitored an adaptation option. Implementation evidence was coded only when a study documented that an adaptation response had been implemented in practice, rather than merely proposed, modelled or recommended. General discussion of management implications or future recommendations without substantive assessment was not classified as adaptation evidence.

Thematic breadth and knowledge co-occurrence

Thematic integration was evaluated using both pairwise theme co-occurrence and a study-level Thematic Breadth Index. For each pair of research themes, co-occurrence was quantified using the Jaccard similarity coefficient[71]:

$$J(A,B) = \frac{|\, A \cap B \,|}{|\, A \cup B \,|}$$

where A and B represent the sets of studies assigned to two themes. Values range from 0, indicating no shared studies, to 1, indicating complete overlap. The resulting matrix was used to identify strongly connected and weakly integrated relationships among research themes.

The Thematic Breadth Index was calculated for each study as the total number of the six themes coded as present, producing a score from 1 to 6. Higher values indicated that a study integrated a wider range of research dimensions.

Associations between thematic breadth and management or adaptation evidence were examined by comparing the proportion of studies containing these outcomes across increasing breadth categories. Because Management Evidence was itself one of the six thematic domains, an additional non-management breadth score was calculated by summing only the remaining five themes. This sensitivity analysis was undertaken to determine whether broader thematic integration outside the management domain remained associated with the presence of management and adaptation evidence, thereby reducing the potential for circularity in the analysis.

Adaptation evidence maturity framework

Two complementary approaches were used to evaluate how the evidence base progressed from hazard characterisation towards adaptation. Here, evidence refers to information reported by a study for a specified component of this pathway. First, a non-cumulative evidence profile was used to quantify how frequently studies addressed key components of the adaptation pathway. Seven components were considered: all studies, drivers, impacts, affected systems, management evidence, adaptation evidence and implementation evidence. Each component was assessed independently, meaning that studies were not required to satisfy preceding components to be counted within later stages. Counts and percentages were calculated relative to the full dataset of 222 studies. Differences between adjacent components were expressed as absolute and percentage reductions relative to the preceding stage to identify where evidence became less common along the risk-to-adaptation pathway, while recognising that the components were overlapping and non-cumulative.

Second, a cumulative adaptation evidence maturity framework was developed to assess how far individual studies progressed through the sequential stages of adaptation evidence. The framework comprised six hierarchical levels: L1, driver evidence; L2, driver and impact evidence; L3, driver, impact and affected system evidence; L4, management evidence; L5, adaptation evidence; and L6, implementation evidence. The framework was cumulative, meaning that a study could only be assigned to a given level when all preceding evidence requirements had also been satisfied. Each study was classified according to its highest completed maturity level, thereby avoiding double counting while preserving the sequential progression of the evidence pathway. For example, a study evaluating an adaptation option but not explicitly assessing

an affected system could not be classified as L5 because the requirements of L3 had not been met. Instead, it was assigned to the highest preceding level satisfying all cumulative criteria.

Pathway and evidence gap analysis

Evidence pathways were visualised using a Sankey diagram linking drivers, impacts, affected systems, management evidence, and adaptation evidence. The Sankey diagram (Fig. 4a) was used to synthesise the connectivity of the evidence base rather than infer causal relationships. Each connection represented study-level co-occurrence, indicating that two components were examined within the same study rather than demonstrating a direct or general relationship. Link weights were calculated as the number of studies in which the connected components were coded together; consequently, wider links represented more frequently reported evidence pathways.

An impact-system matrix was also constructed by cross-tabulating the number of studies linking each impact category with each affected system. The matrix was used to identify both well-established and underrepresented impact-system relationships across the evidence base. For each affected system, the proportion of studies containing management or adaptation evidence was calculated relative to the total number of studies addressing that system. System-specific adaptation proportions were calculated independently by dividing the number of studies containing adaptation evidence for a given system by the total number of studies coded for that same system. Together, the Sankey diagram and impact-system matrix provided complementary perspectives on evidence connectivity and adaptation gaps across the risk-to-adaptation pathway.

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Author contributions

M.Y.G. and D.K. conceptualised the study and developed the methodology and visualisations. M.Y.G. led the formal analyses and data curation. M.Y.G., J.A., S.R. and M.F. conducted study screening and coding. D.K. led project administration and supervision. All authors contributed to writing, review and editing of the manuscript.

Data availability

All datasets used in this study are available within the Supplementary Data files provided with the manuscript.

Competing interests

The authors declare that they have no competing financial or non-financial interests that could have influenced the work reported in this manuscript.

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