communications earth & environment

Article

A Nature Portfolio journal

https://doi.org/10.1038/s43247-025-02428-5

Intermittent estuaries deserve global attention as vulnerable and vital ecosystems

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Intermittently closed estuaries provide important ecosystem services but are often overlooked in coastal and catchment research and management. These estuaries are highly vulnerable to human and climate disturbances due to their episodic closure to the ocean, yet remain understudied. This study maps 2245 intermittent estuaries globally, whose catchments currently support 55 million people, with projections of up to 101 million by 2100. Analysis of three decades of scholarly literature revealed that only 7% of these estuaries have been studied. Research on intermittent estuaries comprises 0.5% of all estuarine literature, despite representing 4–5% of estuaries globally. Major research gaps exist in Asia, South America, and Africa—regions with large, vulnerable populations. Over 90% of research on intermittent estuaries is conducted in (southern) Africa, Oceania, and North America, with most studies focusing on local physico-chemical and eco-hydro-geomorphological processes. This assessment underscores the need to expand research priorities to include ecosystem services, climate and human disturbances, and management, with greater international collaboration and leadership from intergovernmental organisations.

Globally, estuaries are transitional zones where freshwater and saltwater meet, fostering rich habitats that support distinct biodiversity and ecological processes, and offer immense social, cultural, and economic services[1–3]. In wave-dominated, micro-to-low-mesotidal coastal settings, with rivers of variable discharges, estuarine entrances can occasionally or seasonally close, thereby isolating the fluvial and marine environments[4]. These dynamic estuaries are known by various terms worldwide, including Intermittently Closed/Open Lakes and Lagoons (ICOLLs), Intermittently Open/Closed Estuaries, Temporarily Open/Closed Estuaries, Intermittently Closed Estuaries, Seasonally Open/Closed Estuaries, and Bar-built Estuaries[4,5]. In this paper, these estuaries will hereafter be referred to as "intermittent estuaries".

Intermittent estuaries are sensitive due to their fluctuations in entrance state, typically long residence times (when closed), a tendency towards strong stratification, and typically shallow waters[6,7]. Their dynamics are influenced by factors such as weather, tides, wave action, catchment characteristics, fluvial inputs, groundwater discharge, lagoon/barrier size, and morphology[4,8]. As such, even small changes in their physical processes (e.g., wave energy versus fluvial/tidal energy) can induce substantial morphological changes near their entrance, thereby modifying estuarine hydrodynamics and

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triggering cascading effects on eco-geomorphological and bio-geochemical processes, with far-reaching effects for biota and ecological communities[9–12] (also see Whitfield and Elliott[13]). Entrance dynamics in these estuaries are typically influenced by the interactions between wave-driven sediment import and tide/river-driven sediment export[4,14]. An equilibrium morphodynamic state rarely occurs, leading to variations in entrance cross-sectional area, lateral movement, or partial/full closure[15–20]. During periods of low river flow, the reduced fluvial or ebb-tidal energy at the estuary entrance allows wave-driven sediment transport to dominate, intermittently restricting or closing the estuary mouth. High wave energy can facilitate alongshore and cross-shore sediment transport, leading to the formation and maintenance of subaerial beach berms that constrict, or potentially seal, the entrance. Following closure, temporary isolation of the estuary from the marine environment persists until high enough river flows or storm events force a re-opening of the inlet and restoration of tidal conditions.

This responsive nature means that intermittent estuaries (and their associated low-lying human communities) are especially sensitive to anthropogenic pressures (e.g., mechanical opening, land reclamation) as well to the impacts of climate change (e.g., altered hydrology, sea-level rise), typically more so than estuaries with permanently open entrances[21–23]. For instance, compared to permanently open estuaries, intermittent estuaries are predicted to be highly susceptible to the compounded effects of sea-level rise and storm inundation[6,24], and are warming and acidifying more rapidly due to limited oceanic interactions and shallow depths[7]. If located adjacent to urban areas, farmland, or critical infrastructure, closed entrances are often artificially opened to mitigate flooding, prevent excessive algal or macrophyte growth, improve water quality (e.g., reducing nutrient or pathogen levels), and/or promote recreational activities[25–27]. However, abrupt opening of the estuary (whether managed or natural) can lead to sudden changes in water level, current velocities, flushing, salinity, dissolved oxygen, and turbidity, as well as associated variations in morphology and bio-geochemical cycles, causing fish, amphibian, and invertebrate mortalities and shifting food webs and species compositions[28–33].

Despite their widespread distribution and vulnerability to natural environmental and anthropogenic changes, intermittent estuaries have been largely overlooked in broader academic scholarship and coastal management policies and plans. One issue is their omission or marginal inclusion in widely used estuary classifications. Such classifications tend to be based either on geological context (e.g., Hume and Herdendorf[34], according to a large sample of New Zealand estuaries) or their hydrodynamics and salinity dynamics (e.g., Hansen and Rattray Jr[35], Potter et al.[5]). Intermittent estuaries fall between these two approaches and tend to either be neglected or included as special cases of another category (e.g., within the spit-lagoon type of Hume and Herdendorf[34]). One exception is the classification of Roy et al.[36], based on estuaries in southeast Australia, in which intermittent estuaries are a distinct estuary type. Relative neglect of intermittent estuaries can also be attributed to (1) the smaller size of most of these systems, (2) a lack of formative understanding regarding their complex dynamics, with primary research focused on permanently open estuaries, (3) the absence of knowledge regarding the total global distribution of intermittent estuaries and their adjacent human populations, and/or (4) poor global access to relevant grey literature and limited collaboration with Indigenous knowledge holders. Under-representation of intermittent estuaries in large-scale ecosystem assessments exacerbates their marginalisation within national/international research, conservation, and management agendas. For instance, the 2020 International Union for Conservation of Nature Report, "IUCN Global Ecosystem Typology 2.0[20]", is one of the few instances where intermittent estuaries are recognised as a unique ecosystem, though it dedicates them only a single page. Such reports often lack specific management recommendations and do not outline future research pathways, underscoring the necessity for a comprehensive analysis of these systems. At a minimum, such an analysis could determine the geographical distribution of intermittent estuaries and their associated human populations, as well as elucidate critical research themes and their progression across diverse geographic regions.

This study addresses these knowledge gaps and provides the first global assessment of intermittent estuaries and the current state of the science on these systems. Online virtual globes, supplemented with literature mining to determine estuary entrance characteristics (see "Methods"), are used to produce an updated spatial inventory of the global distribution of an estimated 2245 intermittent estuaries. Intermittent estuary locations are then superimposed against the global population distribution to evaluate the present (2020) and projected (2100) number of inhabitants residing in close proximity to these systems ("Methods"). To gain insights into the spatial and temporal evolution of research themes, collaboration networks, and future research and management requirements, a robust search strategy and a supervised filtering process are adopted to capture the full set of relevant peer-reviewed articles published from 1992 to mid–2023 ("Methods"), while recognising that this does not capture the body of literature pre-1992. This approach facilitates a systematic analysis that can be used as a framework for crafting science-based management schemes. Overall, this study addresses the following fundamental questions on intermittent estuaries:

1. What is their global distribution, how many have been studied in the academic literature, and what are the current and projected human populations residing within 10 km of these systems?
2. Which nations and organisations are prominent in the production and funding of relevant scholarly research?
3. What are the prevalent, emerging, and understudied research themes across different geographic regions, and how have they evolved from 1992 to 2023?
4. What does the international collaborative network look like, and what are the potential future research pathways?

This study addresses these inquiries by exploring the recent scientific landscape of intermittent estuaries, pinpointing pivotal priorities for forthcoming research/management endeavours and funding initiatives, and calling for their inclusion in prospective large-scale evaluations of fresh and marine ecosystems.

Results

Global distribution of intermittent estuaries and their populations

A total of 2245 intermittent estuaries were identified across all global coastlines (excluding Antarctica; see "Methods"). Australia (281), South Africa (267), Mexico (202), USA (mainland, 115), and Madagascar (108) have the highest absolute counts (Fig. 1a, Supplementary Table S1, Supplementary Data 1). Georgia (25 sites along 532 km of coastline), Sri Lanka (51 sites along 1124 km), Guatemala (20 sites along 455 km), and South Africa (267 sites along 6238 km) present the highest occurrence of intermittent systems per unit coastal length (Supplementary Table S2). This represents a notable increase in abundance compared to the 1477 intermittent estuaries originally mapped by McSweeney et al.[4]. This increase is attributed to the expanded availability of satellite imagery and improved temporal and spatial coverage. This improved inventory should still be considered a minimum estimate, since the total number of estuaries—let alone the total number that close intermittently—is effectively impossible to determine ("Methods").

The distribution of intermittent estuaries between continents and hemispheres is uneven: South America 24%, Africa 20%, Asia 19%, Oceania 16%, Europe 14%, North America 5%, and the Pacific Islands 2% (Fig. 1b). However, when considering the occurrence of intermittent estuaries per unit of coastal length, our analysis indicates that Africa, the Pacific Islands, and Oceania have the highest densities of these systems (Supplementary Table S2). Most intermittent estuaries (~70%) are found between the latitudes of 20° and 55° (Fig. 1a), with their distribution influenced by the interaction of climate, river flow, and coastal processes[4]. As per Fig. 1a, these estuaries are most common in temperate and semi-arid climates, characterised by major seasonal and interannual variability in rainfall and river

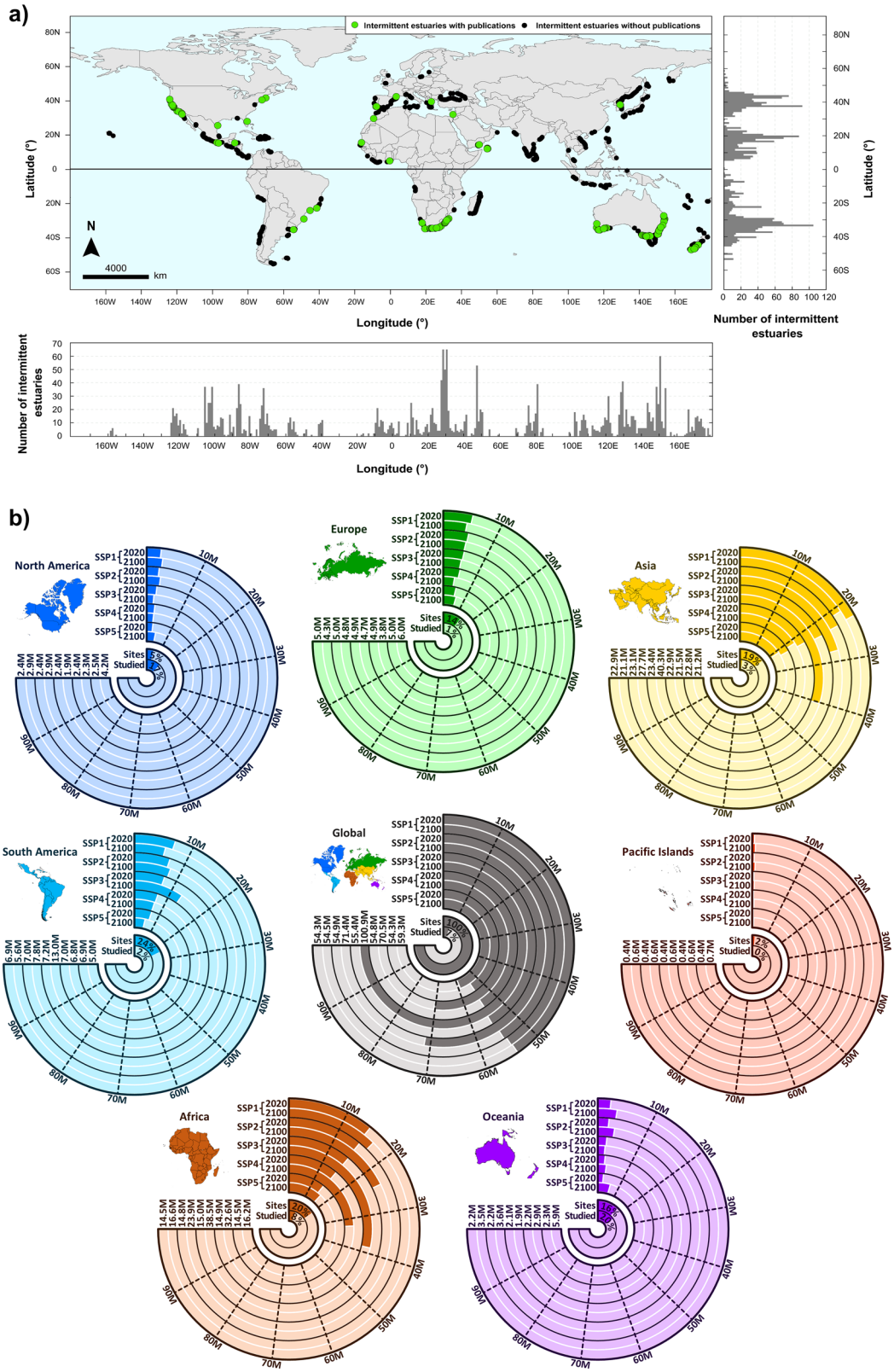

Fig. 1 | Global distribution, research coverage, and population of intermittent estuaries. a Global distribution of intermittent estuaries, highlighting those with recent academic publications (green dots) vs those without (black dots), as well as variability in occurrence with latitude and longitude. In (**a**), the sites with publications refer to those that have been assessed at least once in the academic literature reviewed for this work. **b** Continental and global populations living within 10 km of intermittent estuary entrances in 2020 and 2100 based on various SSP projections (SSP1–SSP5), which consider different combinations of fertility, mortality, and migration patterns ("Methods", Supplementary Table S3). In all panels of (**b**), two smaller inner rings illustrate the percentage of the global estimated number of intermittent estuaries and the percentage by which unique sites in each continent have relevant scholarly publications to date. In all panels of (**b**), the light-shaded areas serve as indicative guide bars, while the dark-shaded areas represent actual population numbers (outer rings), or the percentage of intermittent estuaries and the proportion of unique sites with academic publications (inner rings).

flow. They are also concentrated on micro-to-low-meso-tidal, wave-dominated coasts. This distribution confirms that high wave energy, low tidal energy, and variable river flow (often from small catchments) are most conducive to the occurrence of intermittent estuaries.

Employing a methodological approach in the Web of Science[37,38], we observed that published work on intermittent estuaries accounts for only 0.5% of the total literature on all estuaries ("Methods"), despite representing 4.2% ($n = 2245$) of the estimated total number of global estuaries ($n = 53{,}618$[4]). This under-representation is of concern given their demonstrated vulnerability to climate change and regional development pressures. Of the 2245 intermittent estuaries identified, only 154 sites (~7%) have relevant publications in the post-1992 academic literature (Fig. 1a, Supplementary Data 2). Among these, only the East Kleinemonde River (26) and uMdloti River (14) estuaries in South Africa, and Wilson Inlet (13) in Australia have been the subject of more than 10 published studies in the last 30 years. While approximately 17–20% of intermittent estuaries in North America and Oceania have been the subject of peer-reviewed academic research at least once, this ratio drops to 8% in Africa, and falls below 3% in Asia, South America, Europe, and the Pacific Islands (Fig. 1b). Limited research focused on a few sites might be linked to a spotlight effect[39], where researchers tend to examine locations that already have received attention, established research programs, and substantial datasets.

Our results indicate that intermittent estuaries support a high concentration of human populations (Fig. 1b). These populations are exposed to natural and anthropogenic hazards. Future exposure will depend on population growth and on socioeconomic conditions that can be characterised in scenarios, such as the Shared Socioeconomic Pathways (SSPs)[40]. Following the SSP scenarios[41] ("Methods"), current (2020) and projected (2100) global populations living within 10 km of the entrances of all the intermittent estuaries are estimated to be 54–55 million and 55–101 million, respectively (Fig. 1b). Considering all SSP scenarios used herein, the adjacent global population is forecast to range from near stability to 82% growth by 2100, with increasing percentages ranked as SSP3 82%, SSP2 30%, SSP4 29%, SSP5 9%, and SSP1 0.3% (Supplementary Table S3).

Under all plausible scenarios to 2100, Africa and the Pacific Islands will experience a large increase in populations living by intermittent estuaries by 12–158% and 40–85%, respectively (Fig. 1b). By 2100, Oceania is expected to undergo an estuary-proximal population increase of 31–160% across all SSPs, except for SSP3, under which a reduction of 11% is predicted (Fig. 1b). Populations adjacent to intermittent estuaries in North America are projected to rise under SSPs1–2 and SSP5 (18–68%) but fall under SSPs3–4 (3–22%) (Fig. 1b). Under SSP1 and SSPs4–5, intermittent estuary populations in Asia and South America are projected to decrease by 6–8% and 3–26%, respectively (Fig. 1b). Conversely, population projections for these continents indicate an increase under SSPs2–3 by 20–72% and 11–82%, respectively. In Europe, a reduction of 3–24% in estuary-proximal population is projected under SSPs1–4, with a 20% increase expected under SSP5 by the year 2100 (Fig. 1b). Overall, between 2020 and 2100, Asia (22.8–23.4 and 21.1–40.3 million), Africa (14.5–15.0 and 16.2–38.5 million), and South America (6.9–7.2 and 5.0–13.0 million) are anticipated to host the majority of human residents living around intermittent estuaries, consistently comprising 72–91% of the global populations living near these systems (Fig. 1b). Despite this trend, it is notable that only 8% of intermittent estuaries in Africa and less than 3% in Asia and South America have been the subject of published scholarly research in the last 30 years (Fig. 1b), highlighting a clear gap in our understanding of and ability to manage these systems.

Evolution of research production and funding organisations

From early–1992 to mid–2023, 271 articles and review articles on intermittent estuaries were indexed in the Web of Science ("Methods", Supplementary Data 3). Figure 2a depicts the yearly/cumulative, domestic/international (i.e., determined based on affiliation data provided in each article; publications are considered international if author affiliations list two or more nations), and funded/non-funded articles from 1992 to 2022. Publication output shows a fluctuating upward trend, with 2006, 2015–2016, and 2020–2021 exceeding 15 articles per year (Fig. 2a). The proportion of international collaborative research is typically below 30%. No consistent trend towards internationalisation of research on intermittent estuaries is observed, contrasting with science on climate change more generally, where internationally collaborative research has increased from ~5% to ~60% of the total output over the last three decades[37]. Interestingly, two-thirds or more of the predominantly domestic research received funding (except in 1994 and 1998–1999), likely to support management at local or national scales. Although climate change is a global phenomenon with far-reaching impacts that transcend borders, issues concerning intermittent estuaries are often confined to local or site-specific scales, focusing on the needs of nearby communities. As future threats to these systems intensify, it is crucial to integrate intermittent estuaries into the broader climate and environmental change dialogue to address local challenges more effectively.

Excluding global reviews and theoretical or laboratory-based studies ("Methods"), the distribution of articles worldwide was based on the locations of the intermittent estuaries with publications (Fig. 2b). Between 1992 and 2023, 91% of global research focused on intermittent estuaries within Africa (41.6%) (particularly South Africa at 40.5%), Oceania (34.9%), and North America (14.5%). Overall, intermittent estuaries were studied in 19 nations, with the research spotlight focused on South Africa (40.5%), Australia (30.5%), USA (14.5%), and New Zealand (4.4%), collectively accounting for nearly 90% of the total focus (Fig. 2b). Based on authors' affiliation data from 271 articles retrieved ("Methods"), scholars from 33 nations contributed to the academic literature on intermittent estuaries, with most researchers located in South Africa (34.7%), Australia (24.9%), and USA (14.4%) (Fig. 2c). While Mexico (202), Madagascar (108), Russia (84), India (81), Indonesia (60), Turkey (52), Chile (51), and Sri Lanka (51) host over 50 intermittent estuaries, their total share of academic literature production in this field is less than 2%. The under-representation of scholars and relatively limited peer-reviewed research from most Asian, African (aside from South Africa), and South American countries is notable, particularly given that these continents have the highest number of people living near intermittent systems today and also under future projections (Fig. 1b).

Our analysis of academic articles published on intermittent estuaries from 1992 to 2023 highlights the temporal and spatial evolution in research production, organisations, and funding initiatives (Fig. 2d). From 1992 to 1999, only Oceania contributed to peer-reviewed literature, with universities being the dominant organisations producing research, and 70% of articles receiving funding (Fig. 2d). During 2000–2007, Africa (particularly South Africa—see Supplementary Box B1) emerged as a key region growing their research on intermittent estuaries, contributing to 50% of the research production, while Oceania's contribution dropped to 47% (Fig. 2d). During this period, 87% of articles received funding (90% in (South) Africa and 82% in Oceania). Multi-sectoral research (i.e., research produced jointly by two or more different entities such as universities, research institutes, or government bodies) began to emerge, accounting for nearly one-quarter of the total research output, though universities alone still produced the majority (67%). The government sector, although contributing to only 2% of the research, had all its efforts funded (Fig. 2d). Between 2008 and 2015, Africa continued to contribute to half of the research on intermittent estuaries, with Oceania's share dropping to nearly one-quarter, and North America's contribution exceeding 10% for the first time (Fig. 2d). During this period, research output started to appear from Asia, Europe, and South America, amounting to a 11% share. Nearly 84% of all research efforts were funded, with Asia, Europe, and South America achieving 100% funding, followed by Africa (93%), North America (80%), and Oceania (64%). Universities remained the leading research producers, while cross-organisational research increased to 29%, compared to the previous period (Fig. 2d). An interesting observation was noted in the latest period (2016–2023), where the distribution of research production on intermittent estuaries became more balanced between Africa (33%), Oceania (29%), and North America

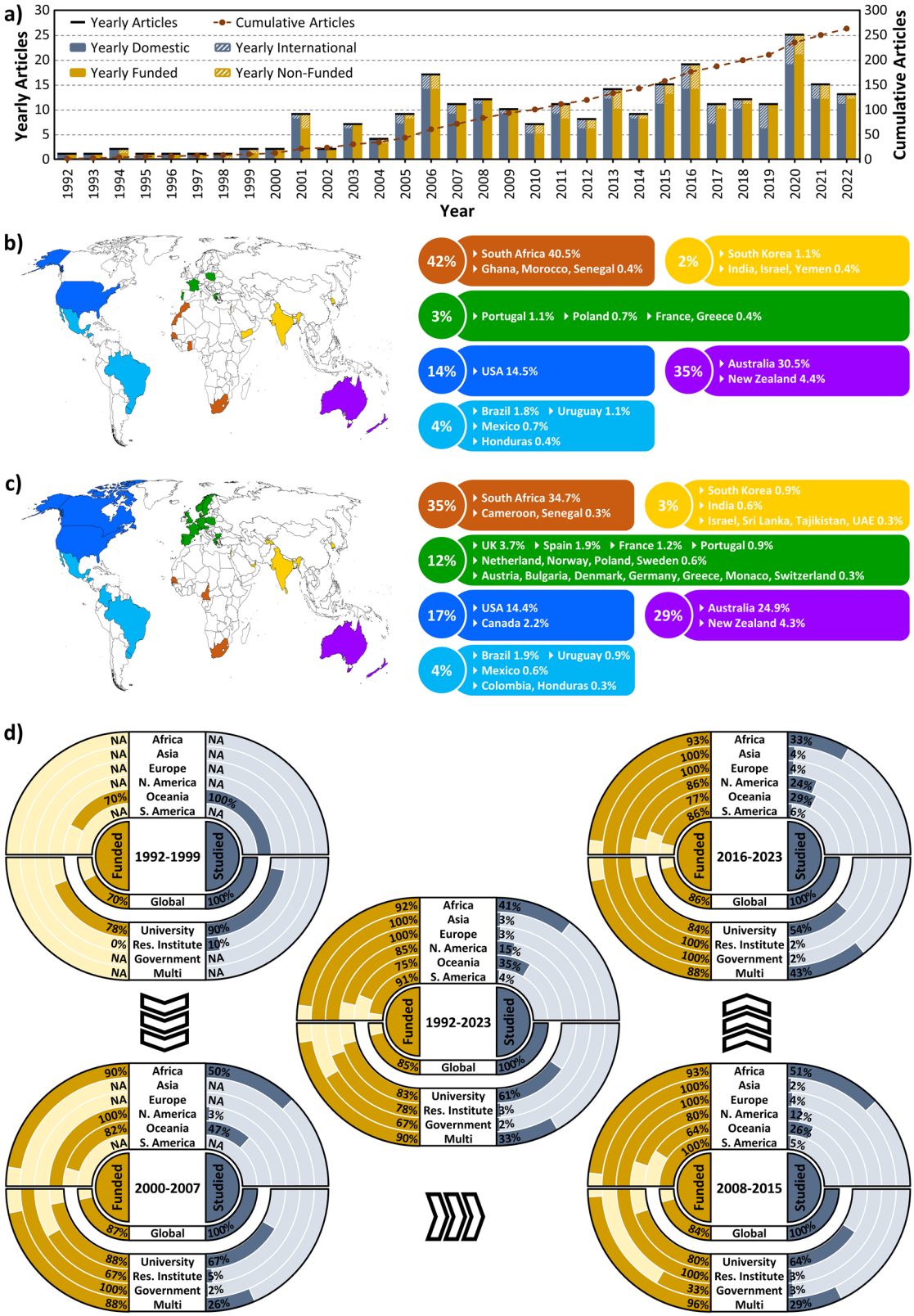

Fig. 2 | Spatiotemporal trends and funding patterns in intermittent estuary scholarly research. a Temporal trends (1992–2022) in the annual and cumulative number of articles, as well as funded/non-funded and domestic/international articles on intermittent estuaries. Only in (**a**), as only eight publications from the first 6 months (not the full year) of 2023 were captured, data from this year was excluded from this visualisation. In (**a**), if the authors listed have affiliations from at least two different nations, the article is considered international; otherwise, it is considered domestic. **b** Geographic distribution of research focus based on locations of intermittent estuaries studied (% of global). **c** Geographic distribution of research authors based on affiliation data (% of total studies). **d** Temporal and geographical evolution in research production/funding across different timeframes, regions, and organisations. In (**d**), for each elliptical plot, yellow (mustard) and grey colours depict shares of funding and studies, respectively, with the top right quarter showing each continent's share of research output, top left quarter the percentage of articles for each continent that secured funding, bottom right quarter illustrating each entity's proportion of research production, and bottom left quarter presenting the percentage of articles from each entity that secured funding.

(24%). Asia (4%), Europe (4%), and South America (6%) increased their collective research share to 14% (Fig. 2d). During 2016–2023, 86% of research received funding, with Asia and Europe achieving full funding for their efforts. A promising trend is the growing prominence of multi-sectoral research efforts, which contributed to nearly 43% of peer-reviewed literature (Fig. 2d).

Overall, from 1992 to 2023, Africa (41%), Oceania (35%), and North America (15%) dominated the production of peer-reviewed research on intermittent estuaries (Fig. 2d). Almost 85% of all studies received partial/full funding, ranging from 75% in Oceania to 100% in Asia and Europe. Universities were recognised as the leading producers of research (61%), followed by multi-sectoral endeavours (33%). No major scholarly contributions from governments and research institutes were detected, potentially due to their output largely being published as grey literature that is not captured by this study (e.g., governmental/managerial reports[42]). Despite Africa being the leading continent in research production, it is primarily due to major contributions from South Africa (Fig. 2b, c), highlighting research gaps in other African countries with intermittent sites (e.g., Tunisia, Ghana). Further, Asia, Europe, and South America contain 1272 (57%) intermittent estuaries, yet their total share of research production is only about 10%. The dominance of research outputs by a few nations, potentially coupled with a focus on local funding schemes to address local-scale problems, highlights the spatial coverage bias in recent academic work (see Supplementary Box B2).

Temporal and geographical evolution of research themes

The evolution of research topics related to intermittent estuaries across various regions and timeframes was analysed for the same 1992 to 2023 period ("Methods") and is presented in Fig. 3. Topics related to physico-chemical characteristics, geomorphology/sediment, marine/terrestrial ecology, and catchment hydrology accounted for nearly 60% of the total research focus, while the least frequently studied topics include ecosystem services (0.5%), management recommendations (6%), climate change impacts (6%), and human disturbances (7%) (Fig. 3). In Africa, across all timeframes, research predominantly examined physico-chemical characteristics, ecology, and geomorphology/sediment (~50–60% of the total focus) (Fig. 3). Asia exhibited a relatively balanced research focus across various themes between 2008–2015, with a recent increase in research on physico-chemical and coastal/estuarine processes during 2016–2023 (Fig. 3). In Europe, research consistently emphasised physico-chemical characteristics and geomorphology/sediment, although the earlier focus on ecology-oriented topics recently shifted towards hydrology-related subjects (Fig. 3). Research in North America concentrated on ecology during the early periods (2000–2007), transitioning to physico-chemical, hydrology, and estuary classifications (Fig. 3). Oceania's research landscape predominantly featured physico-chemical, geomorphology/sediment, ecology, and hydrology, with a recent relative decline in emphasis on the first three topics (Fig. 3). In South America, physico-chemical and ecology were primary research themes during 2008–2023, with a recent increasing emphasis on coastal/estuarine and physico-chemical processes (Fig. 3). Notably, the fewest articles were on ecosystem services (0–3%), management recommendations (4–8%), climate change effects (4–9%), and human disturbances (5–10%).

The above findings can be partially attributed to societal and environmental demands specific to certain timeframes and regions associated with intermittent estuaries. For example, classifications, coastal/estuarine processes, and catchment hydrology constantly accounted for 28–36% of global research focus across different timeframes. These topics are essential for understanding estuarine hydrodynamics, entrance dynamics, and the classification of intermittent estuaries (e.g., based on opening/closing regimes, tidal range, or catchment properties), with practical applications in broader coastal management[21,29,43,44]. While physico-chemical and eco-geomorphology topics generally persisted over time, their total research proportion dropped from 63% in the early years (1992–1999) to 43% during the latest period (2016–2023). At the same time, research on human/climate change disturbances and management has increased with their total share of research growing from 5% during 1992–1999, to 13% during 2000–2007, to 20% during 2008–2015, and to 21% during 2016–2023 (Fig. 3). To explore these 10 topics (Fig. 3), different primary methodologies were designed to help achieve the objectives of studies with different scales and purposes (e.g., case studies, regional assessments). These typically included (1) fieldwork, surveying, sampling, and monitoring (90%), (2) GIS-based tools (8.5%), (3) analytical and numerical modelling (7%), and (4) new technologies (6%) such as satellite remote sensing (Supplementary Table S4). Only 12% of articles (33 out of 271 articles) used more than one methodology.

It is clear that understanding and monitoring physico-chemical characteristics (e.g., water quality) and eco-geomorphology (e.g., vegetation and berm/barrier dynamics) are integral components of research on intermittent estuaries. However, there is an apparent recent shift towards research that aims to support more holistic management strategies by integrating existing knowledge of fundamental topics with responses to anthropogenic and climate change impacts. Despite this shift, academic research on human and climate pressures and management (~20% of research), as well as on ecosystem services (~0.5% of the total research focus), remains limited.

International collaboration and research network

Examining the extent of collaborations across nations reveals the limited extent of international co-publication (Fig. 4a and "Methods"). In total, 25 nations created 128 instances of collaboration, including three nations from Africa, three from Asia, eleven from Europe, two from North America, two from Oceania, and four from South America. Only four nations had more than ten collaborative publications: South Africa (29), USA (16), Australia (15), and the UK (12), with Europe hosting the largest network of collaborations in terms of the number of nations (Fig. 4a). Our findings highlight the limited international collaborations, possibly resulting from the need for estuary management strategies tailored to local and regional contexts. However, growing evidence underscores the importance of international collaboration in addressing overarching global challenges such as climate change, pandemics, and human/environmental health issues[45,46], and it is important to integrate insights from broader global climate and environmental change dialogues into strategies for managing local and regional issues in intermittent estuaries.

The degree of cross-disciplinary research is summarised in Fig. 4b. This analysis assesses if an article considered multiple topics (e.g., an article that investigated coastal/estuarine processes also examined climate change effects). Topics like catchment hydrology and marine/terrestrial ecology are frequently studied in conjunction with geomorphology/sediment and physico-chemical characteristics, with co-occurrence rates of ~50–63%. In contrast, studies of ecosystem services (~0–2%), management (~1–25%), climate change effects (~1–28%), and human disturbances (~0–30%) are less likely to be linked with other topics (Fig. 4b). Out of 271 articles on intermittent estuaries, only six examined ecosystem services quantitatively, mostly in isolation or by sectors (e.g., solely focusing on fishery implications). Excluding the ecosystem services theme, only one out of five articles also considered human and/or climatic disturbances and provided management recommendations.

Discussion

Estuaries are increasingly impacted by human activities (e.g., population growth, catchment hydrology and land use changes, pollutant releases, industrialisation, and over-exploitation of resources/services)[47,48]. Past human impacts are being exacerbated and compounded by growing climate change threats (e.g., rising water temperature/salinity, accelerating sea-level rise, droughts, floods, changing storm characteristics). The drivers of these changes are widespread and transboundary, influencing global populations and degrading nature[7,48–50]. Understanding these impacts requires dedicated research on estuaries that transcends scientific disciplines (e.g., environmental/climate/economy/social/political/engineering sciences) and moves beyond administrative/national borders. For instance, while populations in

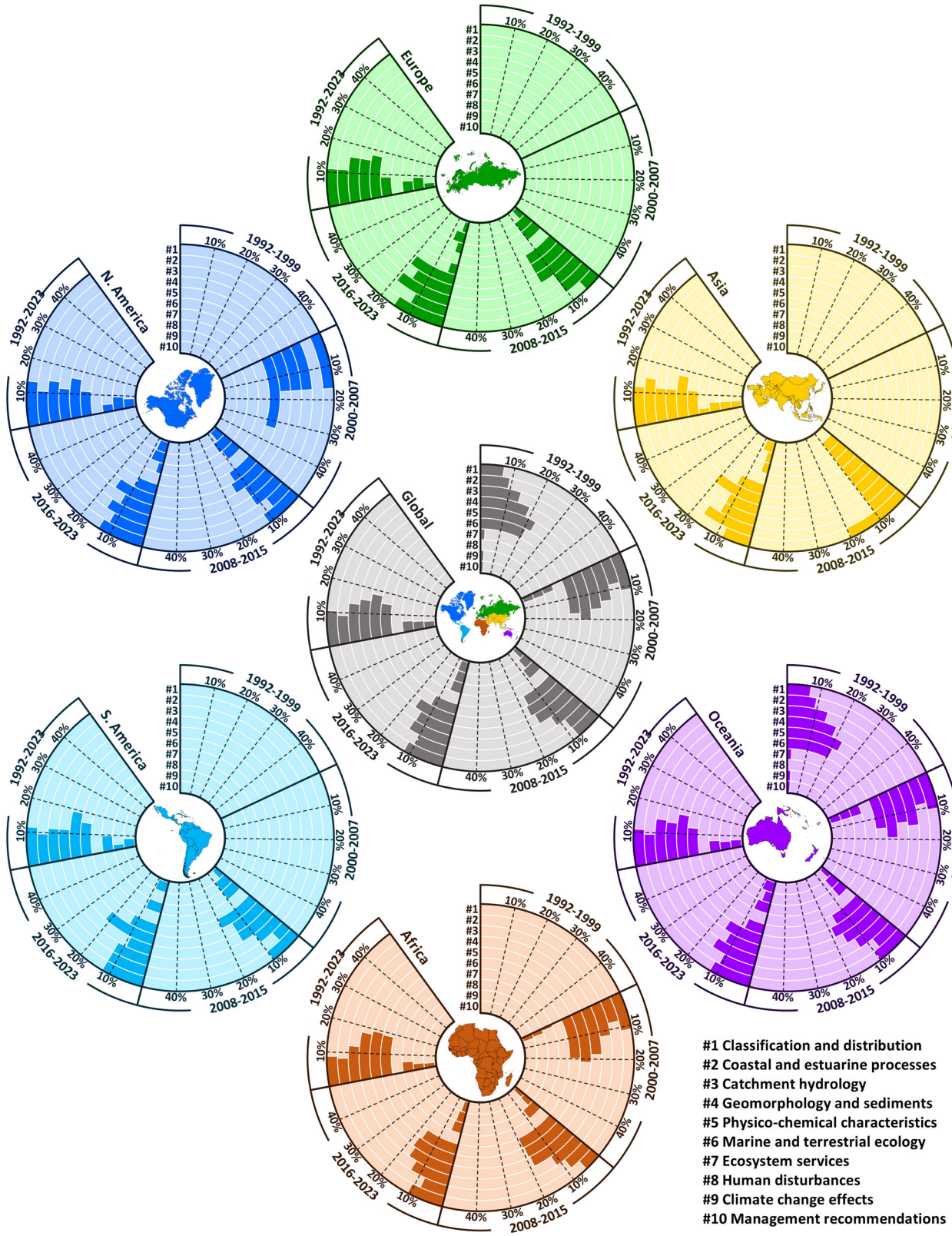

Fig. 3 | Temporal and geographic evolution of research themes on intermittent estuaries. Temporal and geographical evolution of major research themes/topics related to intermittent estuaries across different continents and globally. Analysis spans four timeframes of 1992–1999, 2000–2007, 2008–2015, and 2016–2023 and the full period of 1992–2023, encompassing 10 broad topics: #1 classification and distribution, #2 coastal and estuarine processes, #3 catchment hydrology, #4 geomorphology and sediments, #5 physico-chemical characteristics, #6 marine and terrestrial ecology, #7 ecosystem services, #8 human disturbances, #9 climate change effects, and #10 management recommendations.

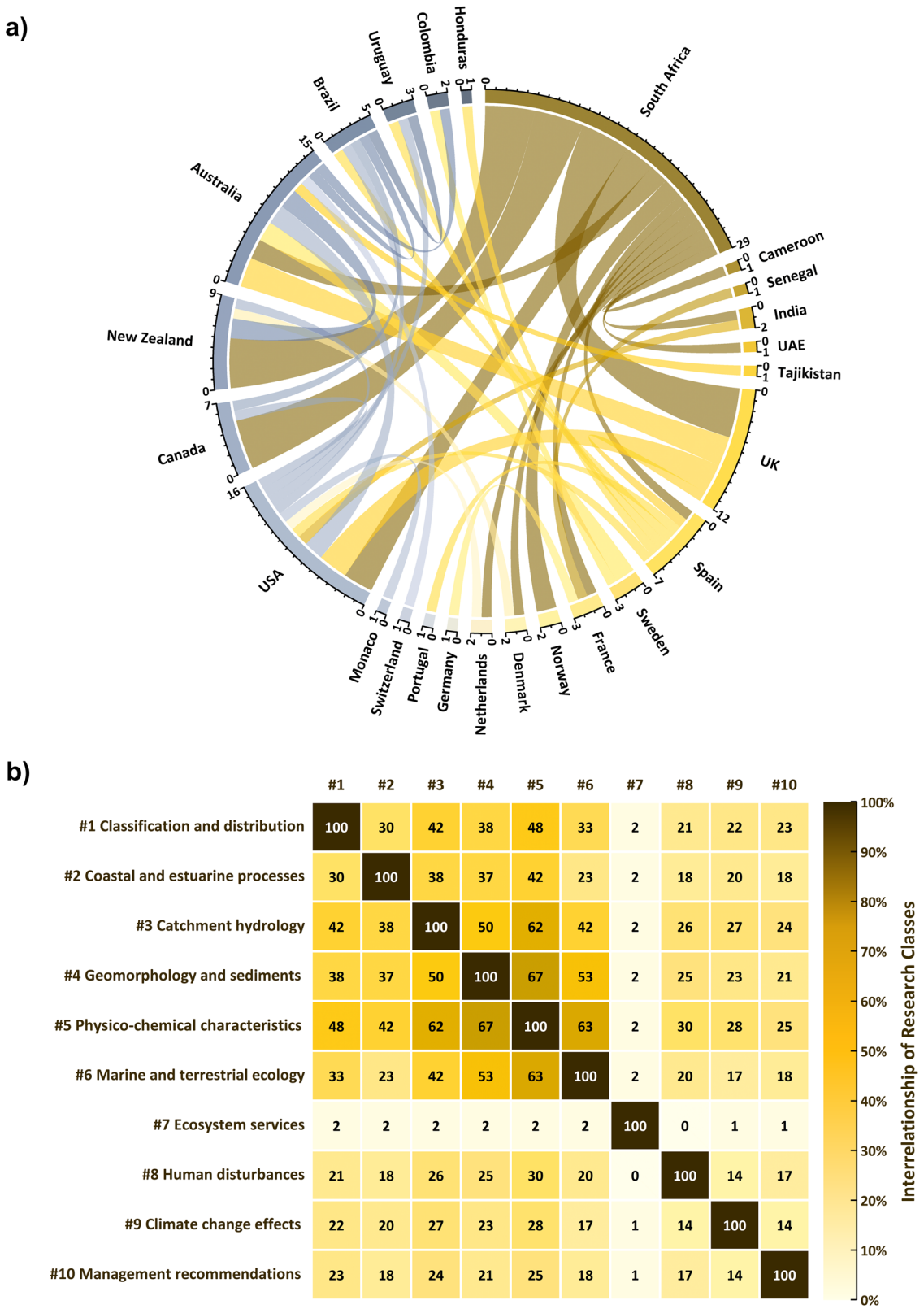

Fig. 4 | Global research collaboration and thematic linkages in intermittent estuary studies. a A country-level network of co-authored research related to intermittent estuaries based on bibliometric information of 271 articles, highlighting limited international collaboration, encompassing only 26 nations, and with only South Africa, USA, Australia, and UK having over 10 collaborative efforts with other nations. **b** A heatmap (in percentage) highlighting the extent to which two research themes are studied together (i.e., co-occurrence of research themes), with darker colours indicating stronger associations and lighter colours signifying thematic gaps in the intermittent estuaries research landscape.

low-elevation coastal zones of developing nations are already recognised to be threatened by climatic and anthropogenic impacts[51–54], the upward trend in populations near intermittent estuaries (particularly in Asia, Africa, and South America) is expected to amplify risks to human livelihoods and health, spur forced displacement and socioeconomic inequality, and damage infrastructure and/or ecosystems. This provides a strong rationale for more research on intermittent estuaries in these at-risk areas.

A recent study[55] found that only about 1% of all climate change research focuses on estuaries, primarily through using modelling approaches. Our results highlighted that studies on intermittent estuaries are predominantly domestic, concentrated on regional sites/areas within a few specific nations, making limited use of modelling approaches and new technologies (only ~6–7% of the total studies—see Supplementary Table S4) to assess current/future states. Existing studies rarely investigate ecosystem services, human and climate impacts, and management requirements. Further, academic literature on intermittent estuaries accounted for only 0.5% of the total literature on all estuaries, despite these systems representing 4–5% of the estimated total number of global estuaries. A recent promising trend is the relatively increased involvement of continents, beyond Oceania and (southern) Africa, in producing multi-sectoral research, along with a gradual increase in topics related to climatic/human pressures and management requirements (Figs. 2, 3).

This article expands upon previous research on intermittent estuaries by documenting a more comprehensive set of global sites and quantifying their human populations. This is supplemented by an extensive investigation of peer-reviewed research conducted over the last three decades. While our contribution provides an in-depth understanding of the research requirements related to intermittent estuaries, further relevant information exists beyond the recent academic literature. For instance, our analysis has not captured the valuable grey literature (e.g., governmental and authoritative reports) or studies published in regional journals, conference proceedings, or book chapters. Further, there are relevant seminal and fundamental publications prior to 1992, with recent research largely building upon them, that have not been investigated here, including a large body of literature on the stability of tidal inlets, including the role and impact of artificial jetties to maintain open entrances[56] (see, for instance, the study by De Swart and Zimmerman[57] and references therein). Hence, a number of naturally ephemeral estuaries may have already been substantially altered and are not captured here. As such, a key next step for estuarine researchers is to review and synthesise this literature to reveal the full diversity of the intermittent estuaries and share insights between regions, including less resourced areas with equally important sites. Overall, our collaborative approach, involving early-career and senior scholars with diverse geographic and expertise backgrounds[58], enhances the robustness of the results and can guide future endeavours.

Intermittent estuaries are complex systems, some of which are already degraded and/or altered, where minor human pressures and climate shifts can have considerable effects. The limited scholarly research on these critical aspects poses challenges for the creation of evidence-based management plans and benchmarking of future changes against historic baselines, particularly for regions where intermittent estuaries are common but understudied (see Supplementary Table S2). These challenges could be addressed by fostering cross-border collaborations, integrating diverse perspectives, and leveraging shared resources. National and international strategies should include sharing data and resources, funding consortia/initiatives dedicated to estuary research, organising more conferences/workshops on intermittent estuaries, integrating research and policy plans at a global scale, and engaging the private sector as a key but currently absent stakeholder. Beyond this, leadership from international multidisciplinary organisations, working in close collaboration with local and regional communities, is essential in promoting further investigations on intermittent estuaries beyond the current limits of the research, ensuring these critical yet vulnerable systems are safeguarded now and into the future.

For instance, an exemplary initiative led by a few Australian, South African, and North American universities was the "2021 International Workshop on Intermittent Estuaries in a Changing Climate[59]", which facilitated critical discussions around the current state of the science on intermittent estuaries and coastal inlets. Such initiatives could be further supported by prominent scientific gatherings such as the American Geophysical Union (AGU), the European Geosciences Union (EGU), Coastal and Estuarine Research Federation (CERF), the Estuarine and Coastal Sciences Association (ECSA), and the Association for the Sciences of Limnology and Oceanography (ASLO).

These platforms could provide unparalleled opportunities for disseminating research, attracting interdisciplinary participation, and driving global awareness regarding intermittent estuaries. To effectively translate the knowledge of these systems into policymaking plans, multinational organisations such as the UNESCO Intergovernmental Oceanographic Commission, the European Union Environment Agency, and the International Union for Conservation of Nature could play pivotal roles. These organisations can facilitate the exchange of best practices and knowledge among member states and beyond, leveraging their authority and resources for the inclusion of intermittent estuaries in national/international environmental agendas, aligning with global sustainability efforts such as the UN Sustainable Development Goals (e.g., SDG 13: Climate Action, SDG 14: Life Below Water). Fostering public-private partnerships may also provide necessary funding and innovative solutions, ensuring that management strategies are both scientifically robust and practically implementable.

Methods

Global distribution of intermittent estuaries

The global distribution of intermittent estuaries was mapped following the methodology of McSweeney et al.[4] to build on the inventory of sites mapped in this earlier study. This involved a thorough inspection of every coastline worldwide, including inland seas, through online virtual globes (namely Google Earth and NearMap), supplemented with literature mining. Historic imagery was examined to determine if an estuary entrance had closed in the past and if it could thus be classified as an intermittent estuary. An estuary was classified as being "intermittent" if its entrance was observed to be both open and closed in the historical imagery record. This basic classification aimed to quantify the total number of intermittent estuaries, understand their distribution, and identify the broad boundary conditions influencing this distribution, without delving into detailed interpretations of their physical attributes and entrance dynamics. All intermittent estuaries identified in the imagery record had at least two historical photographic coverages. As an advancement to McSweeney et al.[4], the imagery used in this study typically covered the past 20+ years, compared to the 10–15 years span in the earlier study. Estuaries were included in the analysis regardless of size and were defined as "the seaward portion of a drowned valley system which receives sediment from both fluvial and marine sources, and which contains facies influenced by tide, wave and fluvial processes[60]". Estuaries were only included if they were present at the outflow of a named river or a clear natural waterway, and this was further examined by interrogating the river name via Google Maps or literature. Urban flow outlets (e.g., human-made drainage canals) were excluded due to extensive modification of their catchments, estuary basin, or mouth channels. Salinity and circulation-based classifications were not considered, as these characteristics could not be assessed from aerial imagery.

The improved inventory of 2245 intermittent estuaries provided herein (see Supplementary Data 1) should still be considered a lower estimate, as accurately counting the total number of intermittent estuaries remains impractical. Further, there will always be some subjectivity in the distinction between estuaries that would be intermittent were it not for engineered interventions (e.g., inlet jetties, dredging), or between contemporary lagoons that have been intermittently open to the sea in the historical past. Online virtual globes have provided opportunities to explore coastlines over the past 20+ years, yet the opening and closure cycles of intermittent estuaries may be characterised by much longer timescales, such that some systems may be excluded. This includes systems that open very rarely, such as during extreme storm surge and/or heavy rainfall events (e.g., coastal lakes in arid

environments such as Western Australia with decadal-scale opening regimes). Some systems may have shifted towards a predominantly closed state (e.g., due to a reduction in tidal prism from reclamation). Conversely, historically unstable inlets have sometimes been stabilised through human-made interventions, such as trained entrances. The global inventory of intermittent estuaries is therefore quite variable at historical timescales.

Current and projected human populations near intermittent estuaries

We estimated the human population residing in close proximity to the intermittent estuaries identified using present and projected future gridded population datasets[41,61]. This identifies the population likely to benefit from the social and cultural values provided by these ecosystems, as well as the number of inhabitants potentially exposed to natural and anthropogenic hazards around intermittent estuaries.

The dataset of global projected populations presented in Wang et al.[41] provides gridded population projections at a fine ~1 km spatial resolution under five SSP scenarios for 2020–2100, with updates every 5 years. This dataset builds on the WorldPop dataset[61], a widely used population product in disaster management studies, city planning, and environmental impact assessments. Using the 2015 WorldPop dataset as the baseline, projected populations are modelled with a random forest approach based on spatial path dependence[62] to reflect the influence of past populations, global land use change[63], and future pathways of social development[64] under different SSPs and other environmental factors (e.g., digital elevation models, slope, distance to cities, travel time).

We produced national-, continental-, and global-scale statistics of the populations residing within 10 km of currently mapped intermittent estuary entrances (2245 sites). Population counts at grid points within 10 km of each entrance were aggregated at the estuary, national, continent, and global scales. A nominal buffer distance of 10 km from the entrance was selected as a conservative proxy indicator[65] to encircle populations living near intermittent estuaries. Grid points located within 10 km of more than one intermittent estuary's entrance were counted only once in the aggregation to avoid double counting at the country level and beyond. It was assumed that the present estuary entrance locations would remain unchanged in the future. Population counts were calculated for the present (2020) and future (2100) conditions under five SSP scenarios depicting a sustainable (SSP1), middle of the road (SSP2), regional rivalry (SSP3), inequal (SSP4), and fossil-fuelled driven (SSP5) scenarios[41]. The SSPs represent future distinct pathways of social development consistent with global climate change research and describe five alternative outcomes of trends in economic development, demographics, urbanisation, and the effects of population change due to natural growth/decline and migration[41].

Search strategy and filtering process

The academic literature on intermittent estuaries was systematically examined using a detailed term-based search scheme, specifically targeting recent peer-reviewed academic literature. This approach did not capture relevant grey literature (i.e., publications not listed in the Web of Science such as governmental reports), other forms of knowledge (e.g., knowledge of resident communities), or articles published prior to 1992 (including some of the classic research on stability of tidal inlets and stratification). Some pre-1990s literature appeared in regional journals, likely due to authors perceiving their systems as region-specific, influenced by the predominance of research from perennially wet climates like Western Europe and the northeastern United States[66]. Overall, the advanced search scheme developed ensured that all key, recent, and relevant scholarly articles on intermittent estuaries were included, while minimising false positives (e.g., discarding articles primarily focused on open-entrance estuaries). Keywords generally relevant to intermittent estuaries were used to create a query string. This query string was then assessed in the Web of Science Core Collection, using the titles (TI), abstracts (AB), and authors' keywords (AK) as the search domains. The search query is presented below:

(TI = ((("Intermittent* Closed/Open Lake* and Lagoon*" OR "Intermittent* Closed and Open Lake* and Lagoon*" OR "Intermittent* Closed-Open Lake* and Lagoon*" OR "Intermittent* Closed/Open Lake* OR Lagoon*" OR "Intermittent* Closed and Open Lake* OR Lagoon*" OR "Intermittent* Closed-Open Lake* OR Lagoon*" OR "ICOLL*" OR "Intermittent* Open Lagoon*" OR "Intermittent* Open Coast* Lagoon*" OR "Intermittent* Open Lake*" OR "Intermittent* Closed Lagoon*" OR "Intermittent* Closed Coast* Lagoon*" OR "Intermittent* Closed Lake*" OR "Bar-Built Estuar*" OR "Bar Built Estuar*" OR "Seasonal* Open Inlet*" OR "Intermittent* Open Estuar*" OR "Closed Estuar*" OR "Closed Entrance Estuar*" OR "Closed-Entrance Estuar*" OR "Restrict* Entrance Estuar*" OR "Intermittent* Estuar*" OR "Closed-Open Estuar*" OR "Closed/Open Estuar*" OR "Closed and Open Estuar*" OR "Restrict* Estuar*" OR "Closed Inlet* Estuar*" OR "Restrict* Inlet* Estuar*" OR "Barred Estuar*" OR "Barrier-built* Estuar*"))) OR (AB = ((("Intermittent* Closed/Open Lake* and Lagoon*" OR "Intermittent* Closed and Open Lake* and Lagoon*" OR "Intermittent* Closed-Open Lake* and Lagoon*" OR "Intermittent* Closed/Open Lake* OR Lagoon*" OR "Intermittent* Closed and Open Lake* OR Lagoon*" OR "Intermittent* Closed-Open Lake* OR Lagoon*" OR "ICOLL*" OR "Intermittent* Open Lagoon*" OR "Intermittent* Open Coast* Lagoon*" OR "Intermittent* Open Lake*" OR "Intermittent* Closed Lagoon*" OR "Intermittent* Closed Coast* Lagoon*" OR "Intermittent* Closed Lake*" OR "Bar-Built Estuar*" OR "Bar Built Estuar*" OR "Seasonal* Open Inlet*" OR "Intermittent* Open Estuar*" OR "Closed Estuar*" OR "Closed Entrance Estuar*" OR "Closed-Entrance Estuar*" OR "Restrict* Entrance Estuar*" OR "Intermittent* Estuar*" OR "Closed-Open Estuar*" OR "Closed/Open Estuar*" OR "Closed and Open Estuar*" OR "Restrict* Estuar*" OR "Closed Inlet* Estuar*" OR "Restrict* Inlet* Estuar*" OR "Barred Estuar*" OR "Barrier-built* Estuar*")))) OR (AK = ((("Intermittent* Closed/Open Lake* and Lagoon*" OR "Intermittent* Closed and Open Lake* and Lagoon*" OR "Intermittent* Closed-Open Lake* and Lagoon*" OR "Intermittent* Closed/Open Lake* OR Lagoon*" OR "Intermittent* Closed and Open Lake* OR Lagoon*" OR "Intermittent* Closed-Open Lake* OR Lagoon*" OR "ICOLL*" OR "Intermittent* Open Lagoon*" OR "Intermittent* Open Coast* Lagoon*" OR "Intermittent* Open Lake*" OR "Intermittent* Closed Lagoon*" OR "Intermittent* Closed Coast* Lagoon*" OR "Intermittent* Closed Lake*" OR "Bar-Built Estuar*" OR "Bar Built Estuar*" OR "Seasonal* Open Inlet*" OR "Intermittent* Open Estuar*" OR "Closed Estuar*" OR "Closed Entrance Estuar*" OR "Closed-Entrance Estuar*" OR "Restrict* Entrance Estuar*" OR "Intermittent* Estuar*" OR "Closed-Open Estuar*" OR "Closed/Open Estuar*" OR "Closed and Open Estuar*" OR "Restrict* Estuar*" OR "Closed Inlet* Estuar*" OR "Restrict* Inlet* Estuar*" OR "Barred Estuar*" OR "Barrier-built* Estuar*")))))

This query string was inserted into the Web of Science Core Collection on 14 July 2023, with the search timespan restricted from 1 January 1992 to 30 June 2023. The search focused solely on articles and review articles written in English, resulting in 406 publications. These publications were carefully reviewed and filtered by the authors in a supervised manner to remove any remaining false positives. For example, articles titled "Drivers of change in shallow coastal photic systems: an introduction to a special issue[67]" and "Suspended sediment dynamics in a deltaic estuary controlled by subtidal motion and offshore river plumes[68]" were discarded, as the former was an editorial and the latter assessed an open bar-built estuary. Upon completion of the filtering process, 271 articles remained, forming the final dataset (see Supplementary Data 3). The majority of discussions in this study refer to these 271 filtered publications, unless explicitly mentioned otherwise (i.e., Figs. 2c, 4a). Note that a limitation of this study is that it relied solely on the Web of Science Core Collection, meaning that some relevant academic publications indexed in other major databases (e.g., Scopus) may not have been included.

To answer the question, "How much of the literature on all estuaries is dedicated to intermittent sites?", a second query string, inspired by Biguino et al.[55], was developed and used to capture peer-reviewed literature related to all estuaries. The following query string was applied:

(TI = (((“estuar*” OR “lagoon*” OR “tidal river*”))) OR (AB = (((“estuar*” OR “lagoon*” OR “tidal river*”)))) OR (AK = (((“estuar*” OR “ria” OR “lagoon*” OR “tidal river*”)))))

This query string was inserted into the Web of Science Core Collection using the same filtering criteria as for the intermittent estuaries literature and returned 81,773 articles. Due to the broad scope of this query, no manual filtering was conducted; hence, this number of articles could be over-/underestimated. The aim of this analysis was to support the discussion points around the ratio of research on intermittent estuaries compared to broader estuarine research. Without any filtering efforts and given 406 articles on intermittent estuaries and 81,773 articles on all estuary types, it could be inferred that the literature that explicitly focused on intermittent estuaries accounted for only 0.5% of the total literature on all estuaries.

Major research topics/themes

A methodological and supervised approach was used to obtain high-level insights into the development of intermittent estuaries literature and its common research themes/topics. In this context, 10 major research themes, inspired by seminal books related to estuaries[48,69–74], were defined using detailed criteria to categorise all 271 articles on intermittent estuaries (Table 1). Each article was carefully reviewed and manually assigned to one or more of the relevant research themes. For example, if a publication assessed sea-level rise impacts on water quality within an intermittent estuary, it was assigned to both the “Physico-chemical characteristics” and “Climate change effects” themes. Once all the articles were classified into relevant research themes, a binary table was created to denote the presence or absence of any given research theme in each article, forming the final dataset for analyses. The evolution of these research themes across different regions and timeframes was scrutinised and presented herein.

Research production, funding organisations, and collaboration network

The metadata for all 271 publications were extracted and analysed either manually or via the Web of Science. This information included publication year, authors affiliations, affiliated institutions/nations, funding organisations, and locations of the studied estuaries. The metadata analysis of the publications over the last 30+ years provided insights into the intermittent estuaries investigated in academic scholarship to date (Fig. 1b), the evolution of domestic and international research (Fig. 2a), global research production and focus (Fig. 2a, b), countries/institutions leading in research production/funding across different regions based on sites studied (Fig. 2d), and gaps related to major research themes/topics (Figs. 3, 4b). These manually created metadata were complemented by bibliometric data extracted directly from the Web of Science, which provided information on the research contributions of scholars from different nations (Fig. 2b) and collaboration links across nations (Fig. 4a).

In Fig. 1a, intermittent estuaries studied to date were identified through a thorough review of all 271 relevant articles, extracting the site(s) examined in each article. In Fig. 2b, global reviews and theoretical/laboratory-based articles were excluded from the analysis/visualisation, as the primary aim was to present the geographical research focus/inequality based on the sites studied to date. In Fig. 2c, research contributions for each nation were evaluated using bibliometric information for all authors’ affiliations in the 271 articles, directly extracted from the Web of Science. Figure 2d was created with the same logic as Fig. 2b, except that all articles, including reviews and theoretical/laboratory-based studies, were included in the analysis. In Fig. 2d, all articles were carefully reviewed, and any acknowledged funding organisations were extracted manually and analysed. In Fig. 4a, a country-level collaboration network was created using the bibliometric information of all 271 articles directly extracted from the Web of Science, highlighting instances where two or more nations produced a collaborative article.

Shoreline and country political boundary data

To quantify the density of intermittent estuaries per country, a ratio of the “total number of intermittent estuaries per country over total shoreline length per country” was calculated (Supplementary Table S2). The total shoreline length of each country was derived from the World Vector Shorelines (WVS) dataset, part of the Global Self-consistent, Hierarchical, High-resolution Geography Database (GSHHG—V2.3.7, June 15, 2017)[75,76].

The WVS is a digital data file at a nominal scale of 1:250,000, containing the shorelines, international boundaries, and country names globally. The shorelines are constructed from hierarchically arranged closed polygons and are available in ESRI shapefile format. The tidal datum used is Mean High Water. The shoreline data are provided at five resolutions:

f: Full resolution—contains the maximum resolution of this data without any decimation.

Table 1 | The major research themes/topics defined in this study, along with the criteria by which any given article on intermittent estuaries is assigned to one or more themes

Research themes	Criteria considered
#1 Classification and distribution	Considered classifications of intermittent estuaries based on geomorphology, size, geology, stratigraphy, hydrography, salinity, and/or energetics.
#2 Coastal and estuarine processes	Assessed coastal and estuarine processes including tide, wave, swell, storm, wind, currents, mixing, circulation, and/or flushing.
#3 Catchment hydrology	Evaluated hydrology of intermittent estuaries through studying rainfall and associated runoff, other inflows, catchment size and characteristics, groundwater, and/or evaporation.
#4 Geomorphology and sediments	Examined sediment properties, sediment dynamics (transport, suspension, etc.), and/or inlet/berm dynamics.
#5 Physico-chemical characteristics	Considered estuarine physico-chemical characteristics including water level/depth, currents, temperature, light, turbidity, salinity, stratification, pH, Chl-a, conductivity, dissolved constituents, trace elements, nutrient elements/concentration, dissolved gases, eutrophication, and/or organic/inorganic matter.
#6 Marine and terrestrial ecology	Investigated bacterial/microbial processes, phytoplankton, zooplankton, flora, fauna, fisheries, birds, and/or food web.
#7 Ecosystem services	Explored ecosystem services including (but not limited to) shoreline/riverbank protection, flood/storm protection, provision of nursery habitats, water filtration, fisheries, and/or blue carbon.
#8 Human disturbances	Studied human disturbances to intermittent estuaries related to urbanisation/developments such as dredging or filling, artificial opening, trained entrances, hydraulic structures, environment flows, land use/cover change, overfishing, wastewater input, agricultural effects, and/or population growth.
#9 Climate change effects	Assessed climatic impacts including (but not limited to) flood/inundation/storm, droughts, altered hydrology, sea-level rise, marine heatwaves, bushfires, rising temperatures, ocean warming, acidification, salinisation, and/or other and compounding extreme events.
#10 Management recommendations	Provided management guidance related to entrance, adaptation/resilience, public awareness/engagement, restoration efforts, dealing with uncertainties, risk indicators, climatic/human impacts, and/or tipping points.

h: High resolution—reduced in size by approximately 80% relative to full resolution using the Douglas-Peucker line reduction algorithm.

i: Intermediate resolution—reduced in size by approximately 80% relative to high resolution using the Douglas-Peucker line reduction algorithm.

l: Low resolution—reduced in size by approximately 80% relative to intermediate resolution using the Douglas-Peucker line reduction algorithm.

c: Crude resolution—reduced in size by approximately 80% relative to low resolution using the Douglas-Peucker line reduction algorithm.

For our analysis, we utilised the h (high resolution) and i (intermediate resolution) datasets. The f (full resolution) dataset was not used due to its greater computational costs and the lack of smoothing, which produced excessively long shorelines. The l (low resolution) and c (crude resolution) datasets were avoided as they overly simplified shorelines (as determined through visual examination in ArcGIS Pro) and underestimated shoreline length. Thus, the h and i datasets provided a good balance between accuracy and computational efficiency. These datasets were mapped at Level 1 (continental land masses and ocean islands, excluding Antarctica), encompassing the ocean-land boundary and all inland seas where intermittent estuaries are present (e.g., Black and Mediterranean Seas).

The h and i WVS shapefiles were loaded into ArcGIS Pro along with country political boundaries (sourced from the World Bank[77]) and the global distribution of intermittent estuaries. A spatial join was performed, converting WVS polygons to lines. For each country with intermittent estuaries, the shoreline length was extracted from both the i and h datasets, bounded by the political borders of each country. A ratio was then calculated using the total number of intermittent estuaries per country divided by the shoreline length (using both i and h datasets) (Supplementary Table S2).

Two alternative shoreline length datasets were considered in addition to the GIS analysis described above: (1) CIA World Factbook[78] and (2) World Resources Institute[79]. Due to the substantial discrepancies in shoreline lengths among these datasets—including some countries with orders of magnitude differences in length, and the lack of clear descriptions regarding the resolution, scale, or degree of shoreline smoothing—we opted to undertake our own analysis for clarity and repeatability.

Data availability

In addition to the datasets provided in the Supplementary Information and Supplementary Data, the underlying data used to generate the figures in the manuscript are available at https://doi.org/10.5281/zenodo.15525709.

Received: 1 September 2024; Accepted: 29 May 2025;
Published online: 06 June 2025

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Acknowledgements
We would like to thank Gorden Jiang from the University of Canterbury for his help with the GIS analysis of shoreline length. Additionally, we appreciate the assistance of Abbas Shamsipour for his contribution to the development of ideas when preparing some of the figures. Our thanks extend to Kym Bilham, Angus Ferguson, and Tracey MacDonald for their constructive comments on earlier drafts of this article. We would like to acknowledge the support from the NSW Climate Change Adaptation Strategy team. We also thank the editors and reviewers for their insightful feedback, which helped improve this article.

Author contributions
D.K., S.R., and S.M. conceived the study. D.K. led and coordinated the work. D.K., S.R., S.M., and R.I. designed and performed the analyses. D.K. and S.M. wrote the original manuscript. D.K., S.R., and S.M. produced the figures and tables. D.K., S.R., S.M., R.I., R.J.N., M.G.H., M.B., J.A., J.L.L., W.G., H.E.P., J.F., J.D., T.A.T., R.C., P.C., and D.H. contributed to the discussion and checked the analyses, as well as reviewed and revised the paper.

Competing interests
The authors declare no competing interests. Danial Khojasteh is an Editorial Board Member for *Communications Earth & Environment*, but was not involved in the editorial review of, nor the decision to publish this article.

Additional information
Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s43247-025-02428-5.

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Peer review information *Communications Earth & Environment* thanks Angel Borja and Hugues Blanchet for their contribution to the peer review of this work. Primary handling editors: Somaparna Ghosh. A peer review file is available.