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Evolution of a river management industry in Australia reveals meandering pathway to 2030 UN goals

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Globally, river management is a multi-billion-dollar industry. The United Nations (UN) Decade of Ecosystem Restoration calls for accelerated action towards integrated, participatory, and adaptive water resources management. Here we test whether the required shifts are occurring in the Australian stream management industry, an environmental management industry in a developed western nation. We undertook structured review and topic modelling of 958 peer-reviewed papers presented at the national stream management conference from 1996-2021. We investigated trends in collaboration, transdisciplinary knowledge, diversity of input and perspectives, adaptive management, interaction with policy, and responses to natural events. We found that the industry has matured over the past 25 years, with increasing collaboration, diversity and interdisciplinarity. However, there was no measurable increase in on-ground community participation or use of adaptive management. The findings highlight opportunities for the industry to mature further to achieve UN 2030 goals for integrated water resource management and ecosystem restoration.

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The last thirty years have seen a transformation in river management, particularly in the western world[1]. Engineering of rivers, streams, waterways, and catchments to reduce flood and erosion risks has given way to environmental management that aims to protect and restore ecological, environmental, social, and cultural values of streams and catchments. Whilst river engineering remains a necessary activity in some places, the science and practice of environment-oriented stream management has grown from aspiration in the 1980s, into a substantial multi-billion-dollar industry[2] comprising a broad range of agencies, institutions, regulators, consultants, and professional organisations.

The last few decades have also seen the development of global goals and initiatives such as the UN Millennium Development Goals (2000–2015), the UN Sustainable Development Goals (2016–2030)[3], and the UN Decade on Ecosystem Restoration (2021–2030)[3,4] These conventions emphasise the urgent need to accelerate the implementation of nature-based water resources management for environmental sustainability. In particular, the UN Decade on Ecosystem Restoration is built upon a recognition that work at local scales, with coordination and support from higher levels of government and non-government organisations (NGOs), is important to build a decentralised global movement[5], and that diverse and collaborative communities of practice are required to build technical capacity[4]. How are nations tracking towards meeting these goals, and is there sufficient enquiry into their water and stream management industries to recommend ways forward? Many UN goals have been reviewed, including water and sanitation[6], but this paper is the first attempt to review the broader question of stream restoration in relation to those goals.

There have been multiple reviews of the success (or otherwise) of projects designed to repair and restore streams across the globe[7–11]. The focus of these reviews has been on the on-ground outcomes of stream management, and the quality of the science that underpins management practices. Here, however, we seek to understand more holistically the stream management industry within which this work is carried out. We use the industry in Australia as an example of an industry operating in a developed western nation. Like other large nations, Australia has a geographically and climatically diverse range of stream types and management problems that need tailored solutions[12].

We analyse the who, what and how of stream management in Australia; the people who manage streams, what they do, and how they apply themselves to challenges, as well as how this has evolved and changed over time. We explore past shifts as the industry has transformed and matured. This sets the context for identifying future challenges and opportunities for the industry and recommending ways forward. To achieve this we analyse proceedings of the long-running Australian Stream Management (ASM) conference[13] for the 25-year period from 1996 to 2021. Over the life of the conference, each presenter has published their work as a refereed six-page paper in the proceedings, and we track changes in the industry by interrogating the ~1000 articles from ten ASM conferences. The ASM proceedings provide an invaluable archive of information and demographics that can be used as a longitudinal study of the history and evolution of river science and stream management. This conference represents the industry through its broad range of participants and authors including academics, government, consultants/practitioners, and community representatives. At the time of our 1996 baseline, the Australian stream management industry was beginning to implement integrated catchment management[14] and involve communities in land and water management (e.g., Waterwatch, Landcare), a model that was being adopted elsewhere[15].

Our hypotheses are guided by what is needed during the UN Decade on Ecosystem Restoration to scale-up stream and catchment ecosystem restoration to the level required to address global environmental challenges, and to meet the UN Sustainable Development Goals including implementation of integrated water resources management at all levels[3,4]. Collaboration between groups with diverse perspectives[16,17], including those groups most affected by ecosystem degradation (e.g., Indigenous people, farmers, women, and youth)[4,5] will be required (i.e., who). Integrating and valuing all types of knowledge[18], including traditional knowledge, practices, and disciplines not usually directly involved in ecosystem restoration[16] will be essential to improving ecosystem health (i.e., what). Implementing adaptive practices (e.g., monitoring and maintenance)[17] and improving resilience to climate change and natural events[19] are needed to make environmental management efforts more robust (i.e., how). Specifically, we use the following hypotheses to test commonly held perceptions of success within the Australian stream management industry:

1. Who: The industry is integrating more diverse perspectives in stream management (as evidenced by the demographics of collaborative authorship teams, the diversity of institution types and affiliations, and gender of authors).
2. What: The industry's work has:
    a. Matured in focus (including nature-based approaches, and incorporation of First Nations and community values).
    b. Become more interdisciplinary (as evidenced by papers on cross-disciplinary topics (integrating biotic and abiotic sciences) and transdisciplinary topics (integrating science and management/policy or community participation)).
3. How: The industry is working in more robust ways, by:
    a. Transitioning from reactive to strategic management in response to natural events (as evidenced by the changing character of papers on droughts and floods).
    b. Increasing influence on policy, and use of adaptive management (as evidenced by papers on these topics).

The findings of our analysis document how this industry has continued to evolve and mature, while identifying gaps, challenges and opportunities. We see this paper as a timely reflection that can be used to report on progress towards meeting global goals and conventions while informing the next phases of stream management evolution. This can only be done by synthesising past trends, interrogating current practices, and identifying remaining gaps and opportunities to build capacity and impactful communities of-practice for the future. This paper provides insights for stream management industries elsewhere, but it is also relevant for a wide range of environmental management industries.

Results and discussion

Who: Is the industry integrating diverse perspectives in stream management? Over the past 25 years, authorship team size has increased (Fig. 1a), suggesting that greater collaboration is occurring in the industry. The proportion of women authors has increased from 18% to 37%, although they are still a minority (Fig. 1b). Cross-institution collaboration has increased, while interstate and international collaboration have remained steady but uncommon (<21% of papers involve interstate collaboration and <8% international collaboration; Fig. 1c). Authorship by consultants has increased, while researcher contributions have

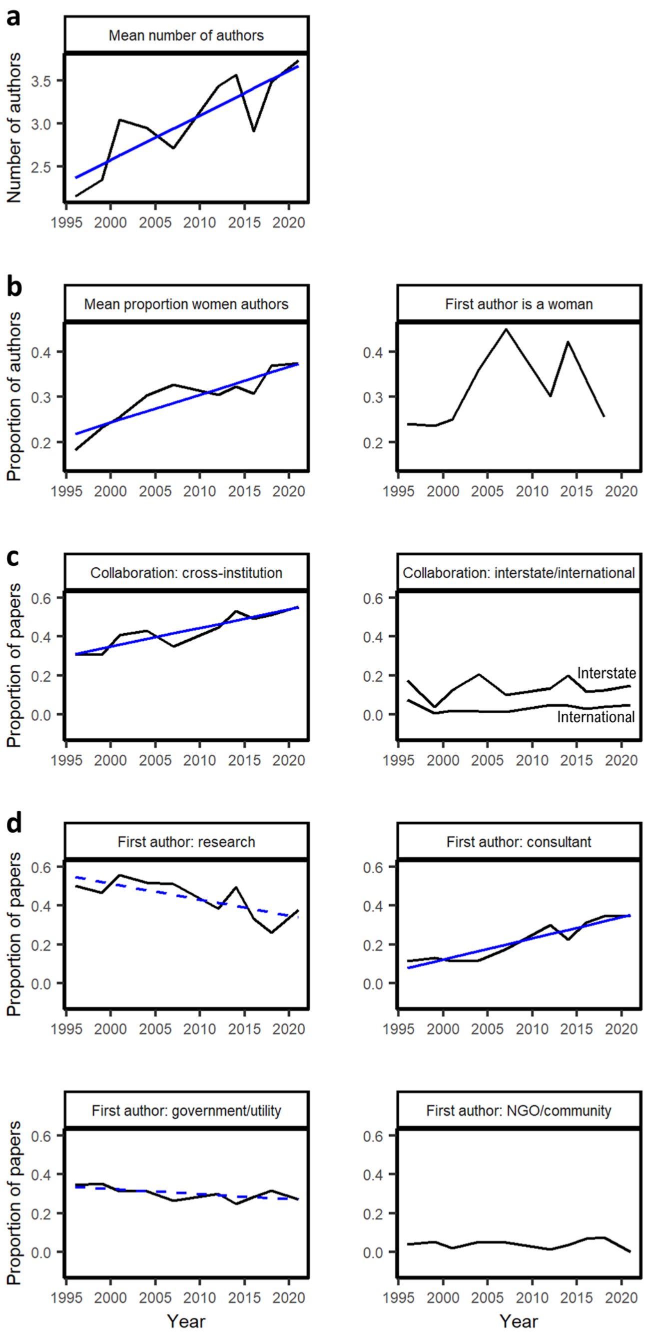

Fig. 1 Trends in author demographics. **a** number of authors, **b** author gender (mean proportion of women in authorship teams, proportion of papers with a woman as first author); **c** collaboration (proportion of papers which are cross-institution, interstate, and international collaborations); and **d** first author affiliations. Research affiliations included universities and research institutes. Government/utility affiliations included all levels of government including catchment management agencies and water utilities. Black lines show data, solid blue lines indicate trends with $p < 0.01$ (considered here to be significant trends), dashed blue lines indicate trends with $0.01 < p < 0.05$ (considered here to be trends supported by weak evidence).

declined (Fig. 1d), reflecting a shift in the industry from academic pursuits to applying findings and translating theory into practice. This trend also aligns with increased outsourcing to consultants[20], staffing declines in research institutes, and shifting funding priorities within the public sector. Government employees, particularly those working in local authorities such as utilities and catchment management agencies, as well as local and federal government have, over time, increased their representation as authors but decreased their representation as first authors. State government representation as first authors declined from 25% at 1ASM to 11% at 10ASM. Representation of community members or NGOs as authors has remained low throughout.

At 1ASM, academics and consultants were overrepresented as authors, while government employees tended to be under-represented (Fig. 2, Supplementary Table 2). Government-employed attendees tended to be audience members rather than authors and presenters at earlier conferences. By 10ASM, delegate and author distributions were more comparable with attendees from diverse institution types contributing as authors, enhancing multi-directional, inter-institution knowledge flows.

Collaboration networks have become broader and stronger over time (Fig. 3). In 1996 there was little collaboration between different types of institutions, but by 2021 collaborations were occurring between almost all institution types. Across the years, collaboration between universities and consultants remained strong, while collaboration between consultants and state governments became even stronger. While NGO/community representation remained small, there was an increasing trend in their collaboration with consultants and universities. The increasing representation of catchment management groups, utilities, and local government also suggests greater localisation of stream management efforts, but these groups are not collaborating with other institutions as co-authors of conference papers, suggesting they are not collaborating in practice.

What: How has the focus of the industry's work matured? The content of material published in the proceedings has become increasingly diverse over time, attesting to the breadth of the industry and the work that is being conducted (Fig. 4). Strong positive trends in topic prevalence have occurred for waterway management programmes (topic 1) (topic numbers in parentheses throughout this article refer to Fig. 4), water and mining (topic 2), and environmental water planning and evaluation (topic 3). There was a weak but positive trend towards greater incorporation of indigenous river management (topic 6), although overall prevalence of this topic remained low.

Papers reporting on specific topics have varied over time as the latest innovations and concepts come in and out of favour or become common practice and routine. For example, willow and vegetation management (topic 59) peaked as a topic in 1996–1999 then declined to low levels over the remainder of the period. Advances in understanding the impacts of exotic willows on Australian rivers[21] produced clear guidance[22] which made willow management routine. Similarly, innovative programmes such as Waterwatch and Landcare that began in the late 1980s and early 1990s are now a routine part of stream management in Australia. Such topics are now being replaced by newer community initiatives such as citizen science on environmental DNA (eDNA) projects (i.e., topic 11: platypus, eDNA and citizen science). Overall, community participation in river management (incorporating topics of indigenous river management (topic 6), platypus, eDNA and citizen science (topic 11), landholder participation (topic 22), and community programmes (topic 58)) has remained steady over time (see Fig. 5a). The rise of remote sensing (topic 4) in stream management and monitoring, and eDNA programmes also illustrates the influence of new technology and science on the industry.

More sensitive, nature-based approaches to stream management were already well embedded in Australian stream

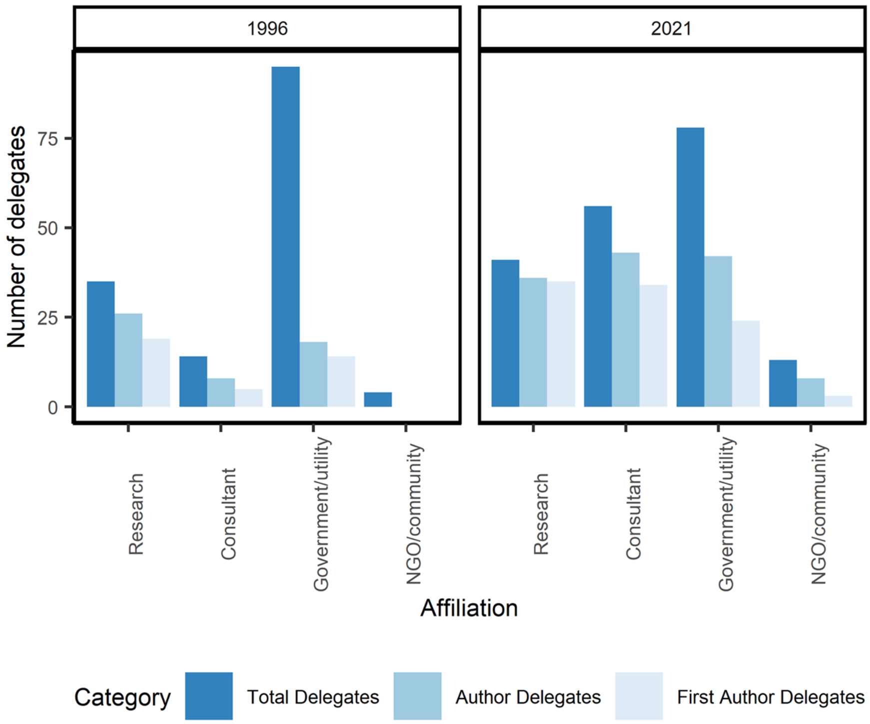

Fig. 2 Delegate affiliation categories and representation as authors in 1996 and 2021. Total delegates are shown in darkest blue, delegates who were also authors in mid blue, and delegates who were also first authors in lightest blue. Researcher delegates remained strongly represented as authors over time, while consultant and government representation as authors increased. Note that for the 2021 conference (which was held online), delegate representation was similar to the 2018 conference which was held in person (see Supplementary Table 2).

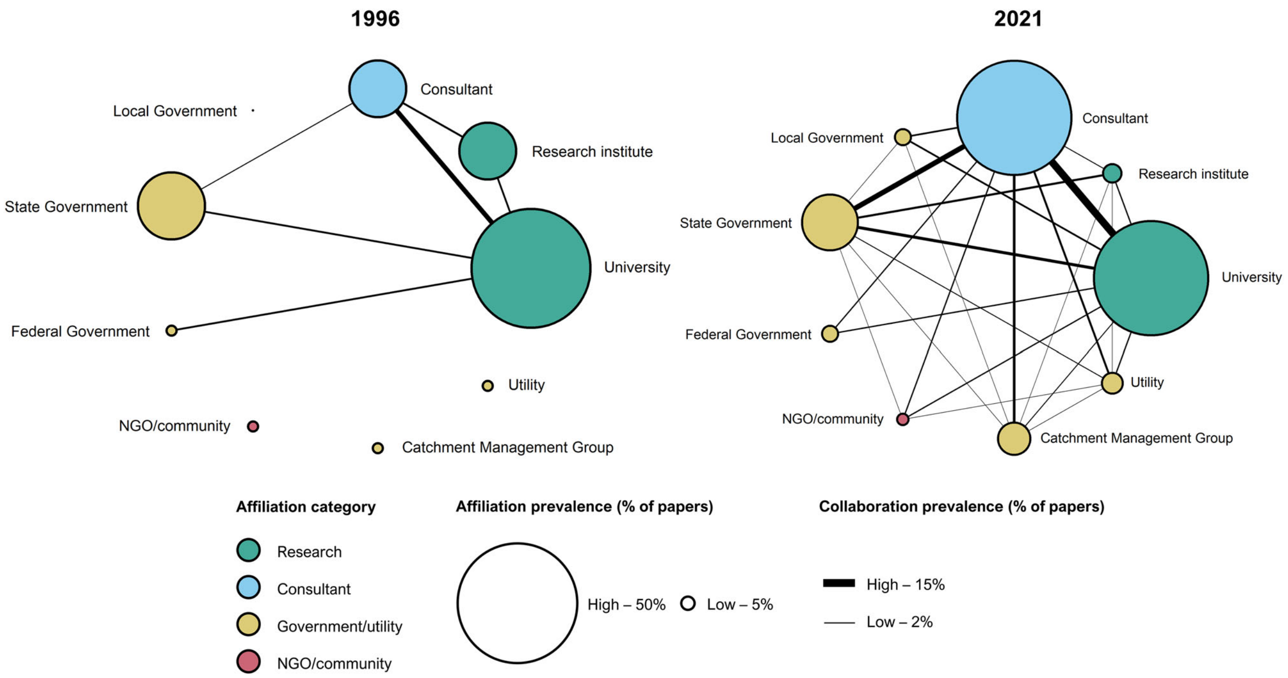

Fig. 3 Collaboration networks were broader and stronger in 2021 than 1996. Diameter of nodes indicates proportion of papers with each affiliation type represented, while the width of the lines linking nodes indicates the proportion of papers with collaboration between affiliation types. For example, a paper with authors from two institutions will have both institutions counted and one collaboration between them counted (therefore proportions do not sum to 100%). Nodes are coloured by affiliation category (research in green, consultant in blue, government/utility in yellow, and NGO/community in orange).

management practices by 1996 and have remained steady over time. For example, topics such as geomorphic character and recovery (topic 25), riparian land management (topic 31), and river rehabilitation planning (topic 35) have been a feature of all ASM conferences. Discussion of topics such as the use of large wood (topic 53) and bank erosion and vegetation (topic 57) have decreased as nature-based techniques become common practice. On engineering topics, there was no trend for bed protection

Fig. 4 Topic prevalence over time. Black lines show topic prevalence, solid blue lines indicate trends with $p < 0.01$ (considered here to be significant trends), dashed blue lines indicate trends with $0.01 < p < 0.05$ (considered here to be trends supported by weak evidence). Topics are ordered by the strength of the trend, from highest positive at the top to highest negative at the bottom. Topic labels are coloured by discipline (abiotic science in dark green, biotic science in orange, community participation in purple, integrative science in pink, management and policy in light green). For details of topics, see Supplementary Table 3.

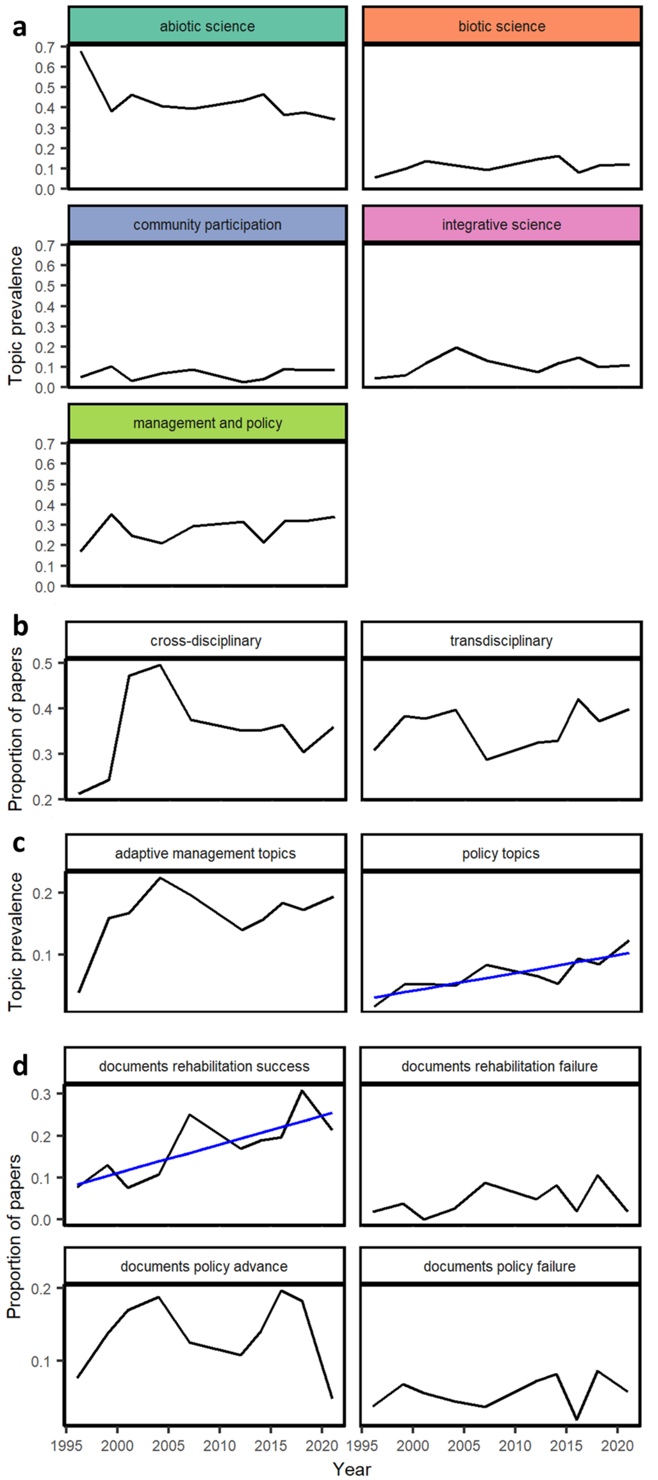

Fig. 5 Trends in disciplines, interdisciplinarity, policy, and adaptive management topics. a topic prevalence aggregated by discipline (coloured by discipline as per Fig. 4, Fig. 6); **b** proportion cross-disciplinary and transdisciplinary papers; **c** prevalence of topics on adaptive management and policy; **d** proportion of papers which document rehabilitation success/failure (as indicators of adaptive management), and policy advances/failures. **a**–**c** are derived from topic modelling results while **d** is derived from structured review. Black lines show data, solid blue lines indicate trends with $p < 0.01$ (considered here to be significant trends). There were no trends with $0.01 < p < 0.05$.

structures (topic 36) or bank protection structures (topic 41), and a weak positive trend for waterway design (topic 9) over time. After a dramatic early drop, the topic prevalence of bank protection structures (topic 41) has remained low.

What: Has the industry's work become more interdisciplinary? From initially being dominated by abiotic science in 1996, the conference quickly transitioned to inclusion of a greater array of disciplines (Fig. 5a). The proportion of papers that were cross-disciplinary (integrating biotic and abiotic sciences) peaked in 2001–2004 then stabilised to around 30–40% thereafter (Fig. 5b). The proportion of transdisciplinary papers (integrating science and management/policy or community participation) has fluctuated around 30-40%, first peaking from 1999–2004, then dipping in 2007 before increasing again.

Increases in some cross-disciplinary and transdisciplinary topics (e.g., remote sensing (topic 4); platypus, eDNA and citizen science (topic 11), see Fig. 4) can be attributed to external forces of technology development. There was no trend in other cross-disciplinary science topics such as data and decision support tools (topic 13), stream condition assessment (topic 28), and environmental flow regimes (topic 33), or topics incorporating management and policy such as leadership and ways of working (topic 26), governance and knowledge in adaptive management (topic 27), river rehabilitation planning (topic 35), or ecosystem services (topic 49). However, transdisciplinary topics such as urban stormwater management (topic 5), indigenous river management (topic 6), and flood risk management (topic 14) did show a weak positive trend.

Associations between the top 20 topics (measured as the cosine similarity between prevalences in each paper) at the 1996 and 2021 conferences are shown in Fig. 6 (see Supplementary Figure 1 for the other 8 conferences). In 1996, strong associations were present between topics in the same domain, e.g., within the abiotic sciences. By 2021, topic associations were overall weaker, but some associations were being made between scientific, management/policy, and community participation domains, indicating greater transdisciplinarity. However, some topics that were expected to be cross-disciplinary or transdisciplinary were not associated with other topics (e.g., waterway design (topic 9), leadership and ways of working (topic 26); Fig. 6).

How: How does the industry respond to natural events? As with most rivers in the world, Australian rivers are shaped by droughts, floods, bushfires and other events, that also influence waterway management responses and interests. After an initial spike in post-event discussion, drought, flood and fire tended to be a constant topic of interest in the stream management industry. For example, the millennium drought in 1996–2009 sparked a raft of scientific advances and policy reforms (e.g., the National Water Initiative reform agenda (2004) which included formal provisions of water for the environment[23]). Environmental flow regimes (topic 33) were most prevalent in ASM conferences in the early 2000s, while discussion of water reform (topic 38), that was largely a response to water scarcity and overallocation, peaked in 2007 (Fig. 4). Discussion of environmental watering of flow-stressed rivers (topic 12) and regulated rivers and environmental flows (topic 34) peaked in 2012 while discussion of environmental water planning and evaluation (topic 3) followed, peaking in 2021, indicating a progression from scientific knowledge to management and policy advances, through to feedback from monitoring and evaluation programmes being shared within the industry.

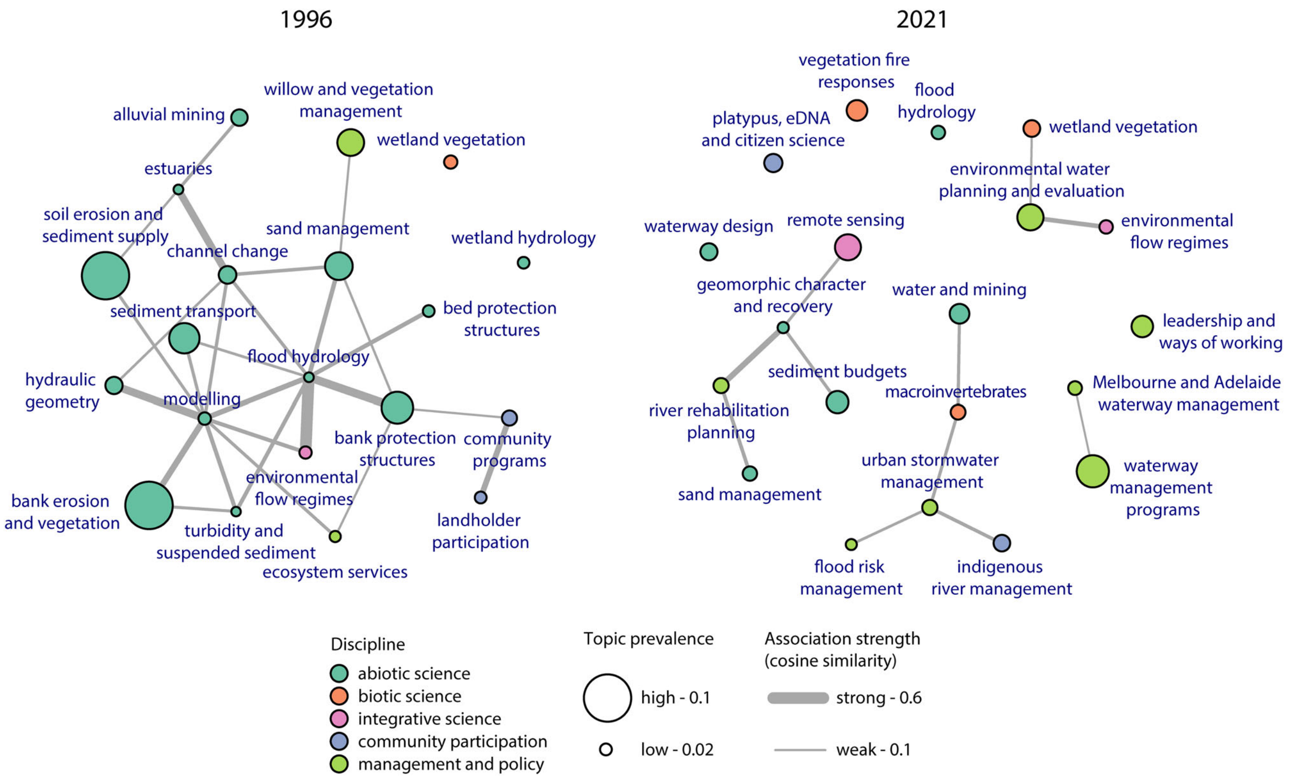

Fig. 6 Associations between top 20 highest prevalence topics were stronger in 1996 than 2021. Association strength, calculated as cosine similarity between vectors of each topic's prevalence in each paper, is indicated by line weight. In 1996, strong associations mostly occurred between topics in the same domain (i.e., abiotic science), whereas in 2021, associations were mostly between different groups including management/policy and community, indicating stronger transdisciplinarity. Node diameter is scaled by topic prevalence, and node colour indicates discipline (abiotic science in dark green, biotic science in orange, community participation in purple, integrative science in pink, management and policy in light green). Detailed topic descriptions are presented in Supplementary Table 3.

Discussion of flood hydrology (topic 24) peaked in 2012 (Fig. 4) following the La Niña years of 2010–2012 which resulted in severe flooding in eastern Australia and north-western Western Australia[24]. Flood risk management (topic 14) became a dominant topic at the 2012 6ASM and remained so in the following conferences up to 10ASM in 2021, indicating that rapid knowledge creation and dissemination about the science of flooding was followed by a decade of sustained discussion about improving management for future floods. Subsequent floods on the east coast of Australia (e.g., Queensland/New South Wales 2013, Lismore 2017, Townsville 2019) kept the topic on the agenda and allowed ongoing development and testing of management strategies.

Discussion of vegetation fire responses (topic 7) peaked in 2012 and again in 2021, after major and widespread fire events in 2003, 2008–2009, and 2019–20 in south-eastern Australia. There was little discussion of bushfire after the 2003 event; it seems that post-fire impacts on catchments and streams did not become a major part of the ASM industry until several post-fire flood and erosion events had occurred (i.e., 2003, 2007 and 2009[25]), indicating that this was not an isolated event but a growing problem requiring an ongoing scientific and management response.

How: Is the industry using adaptive management, and influencing policy? Stream management in Australia has adopted and used adaptive management in the last 25 years, but has not yet fully transitioned from a passive model to an active, proactive model[26]. Overall, adaptive management topics rose in prevalence from 1996 to 1999, peaked between 2004 and 2007 and have stayed steady thereafter (Fig. 5c). Focus on monitoring, evaluation and reporting frameworks (e.g., data and decision support tools (topic 13), stream condition assessment (topic 28) and river values in condition assessment (topic 54)), occurred in the early 2000s, but this trend was not sustained (Fig. 4). Planning was represented in several topics including environmental water planning and evaluation (topic 3), landholder participation (topic 22), and river rehabilitation planning (topic 35) all of which grew in prevalence over time.

Other parts of the adaptive management cycle (e.g., vision-setting, adjusting) were less strongly represented, indicating that there are limitations which are preventing the full adoption of proactive adaptive management. For example, prioritisation, an important precursor to adaptive management, was not common enough to be identified by our algorithm as a topic. Vision-setting was only represented in the topic river rehabilitation planning (topic 35) with no trend over time. The adoption and use of adaptive management can be examined through the documentation of failures. Over time there has been an increase in stories of stream rehabilitation success, but papers discussing rehabilitation failure remained rare (Fig. 5d). Perhaps this reflects a positivity bias in the industry and an unwillingness to share lessons from failure. This is a gap in the Australian adaptive management system. The same trend emerged for policy topics. Papers that document policy advances outweigh those that document failings.

Placing findings in a global context. The science and policy of stream management in Australia can be considered reasonably similar to that in North America and Europe. Like elsewhere (e.g., United States[27], New Zealand[28], United Kingdom[29]), we found that the industry is integrating more diverse perspectives, with greater collaboration and greater multi-directional knowledge sharing. The increase in consultant representation and collaboration between researchers and consultants is a global trend (see Casas-Mulet, et al.[30] for an example from an international ecohydraulics symposium), and reflects the rise of private sector participation in knowledge creation and dissemination in neoliberal economies[31]. The strong central core of collaboration that we observed between government, researchers and consultants indicated integration of knowledge creators and end-users that differed from the ecohydraulics discipline[30], although that could reflect the greater emphasis on management at ASM compared to more scholarly international symposia. Government-researcher collaboration has also been observed to be strong in research priority-setting for conservation and ecology[32]. Stable and reasonably high rates of cross-disciplinary and transdisciplinary work (~35% of papers each) contrast with findings of low interdisciplinarity of the scientific field of river research[33], suggesting that better integration of disciplines is occurring in the broader industry than the scientific literature. There are still major gaps in integration of First Nations and community perspectives, as has been found globally[34], although counter-examples exist such as Māori co-management of New Zealand's rivers[35].

Furthermore, unlike in other places (e.g., Europe[36]), application of nature-based solutions does not appear to have increased over time in Australia although certain topics framed around techniques (e.g., use of wood and vegetation) rose and fell as they were either incorporated into standard practice, or fell from favour. In some topic areas, such as environmental flows and flooding, there has been a maturing of discussions over time, from sharing of scientific knowledge as it was generated, through to development and implementation of management practices and policy. There is some evidence of increasing communication about policy topics, although policy advances were discussed more frequently than failings or challenges. This bias towards success was also present in discussions of rehabilitation outcomes, indicating that the industry is not yet embracing an adaptive management system that explores failures and mistakes. The results showing poor influence on policy and poor uptake of adaptive management are not dissimilar to stream and environmental industries elsewhere (e.g., US[37], Europe[38]).

Limitations of findings. The findings are derived from a knowledge-sharing forum that brings together a subset of the Australian stream management industry, mainly from the more populous, south-eastern states. Every text dataset has biases related to author characteristics and external drivers (e.g., conference topic, journal scope). Unlike many published proceedings and journals (e.g., International Symposium on Ecohydraulics[30]), the ASM conference is not heavily biased towards academic contributions, but includes high proportions of government and consultant authors. While some theoretical advances in river science are likely missing from the dataset, the bias towards practical application of stream management means that trends or gaps revealed by analysis of the proceedings can inform the future direction of the broader industry (not just the scientific discipline). Geographic bias in the authorship and attendance at the conference mean that the findings may not be representative of river management in under-represented states such as Western Australia, South Australia and the Northern Territory. Furthermore, Aboriginal and Torres Strait Islander peoples are under-represented at ASM, and Indigenous knowledge and practices in use in stream management are poorly captured in the ASM papers.

Conference themes might have a minor influence on the trends we see in the data. They can provide subtle influence on particular topics and/or vocabulary for particular conferences (e.g., discussion of floods at the 2012 conference which had the theme 'managing extremes'), but any such shifts do not markedly alter the long-term, 25-year trends for these variables. It is unlikely that conference theme meaningfully influenced the more sustained trends for authorship demographics, collaboration, industry structure and disciplinarity.

Progressing on UN Ecosystem Restoration and Sustainable Development Goals in Australia and globally. UN goals provide a useful formal framework to situate the results of this analysis. The UN Decade on Ecosystem Restoration is upon us[4] and the UN Sustainable Development Goals (SDGs) have been set and reported upon[3]. UN Sustainable Development Goal 6 is 'ensure availability and sustainable management of water and sanitation for all'. Target 6.5 argues to urgently 'implement integrated water resources management at all levels'[3]. Australia already has a high degree of implementation of this goal[3], but urgent and accelerated action is required to meet the 'very high' level benchmark set as the 2030 target.

This paper provides a detailed analysis and an objective retrospective review of the state and trajectory of stream management in Australia from which to interpret trends, identify remaining barriers to progress and areas where transformative change is still needed. By exploring past trajectories, the stream management industry can strategically plan and implement actions to achieve the UN SDGs. It could be argued that we know enough and that it is time to use this knowledge in smart and new ways, consolidate what we know and increase our capacity building to make the step-change needed to achieve global goals. Scaling up from local to global is a key tenet of the UN Decade on Ecosystem Restoration[4]. By situating our findings in the context of UN goals we conclude this paper by providing key recommendations that can drive stream management evolution (Fig. 7).

Recommendation 1: Work holistically to create communities of practice. The industry and society must work holistically to restore the relationship between humans and nature (including rivers) to fully implement integrated water resources management (UN SDG Target 6.5). Inclusion and participation of diverse communities and stakeholders in stream management must continue to increase, creating more integrated and active communities of practice. Transdisciplinary work which integrates the community can be challenging but tends to result in better outcomes[39], and ways to overcome these challenges are becoming better understood[40]. In Australia, as elsewhere, the inclusion and integration of First Nations traditional knowledge and practices is vital and urgent[41]. Other barriers to community participation also need to be broken down[42].

Recommendation 2: Implement nature-based solutions. Rehabilitation techniques still need to transition fully towards nature-based solutions and away from command-and-control engineering[43–45]. Nature-based solutions need to be applied at appropriate scales and to large-scale conservation and rehabilitation initiatives to prevent, halt and reverse riverine ecosystem degradation, and enhance the environmental, societal, cultural and economic benefits and services provided by healthy riverine environments (in line with UN SDG Target 6.6, 'protect and restore water-related ecosystems'). There is a need to unlock society and the industry from the cycle of restoration persistence – continually (re)investing in maintenance of unmaintainable or inappropriate strategies[46].

Fig. 7 Five recommendations to support progress towards United Nations (UN) Sustainable Development Goals (SDGs) over the Decade for Ecosystem Restoration to 2030. The five recommendations (in outer green circles) support broader UN goals (in central blue circle), including SDG Target 6.5, 'implement integrated water resources management at all levels', and SDG Target 6.6, 'protect and restore water-related ecosystems'.

Recommendation 3: Substantially improve stability and resourcing of the industry to implement proactive adaptive management. The industry must advocate for stable, long-term investment and resources that enable the full adoption and implementation of active, proactive adaptive management whereby the focus is on learning through experimentation, and implementation is designed to test hypotheses to improve best practice[26]. The full integration and use of visioning, monitoring, evaluation, reporting, communicating and adaptation in practice is needed. Open access, globally available repositories of data, techniques, and case studies (that are accessible to practitioners and community, not just academia) could provide a starting point for this. A willingness to examine, and be transparent about, failures in on-ground management is also needed, requiring cultural change in institutions and knowledge-sharing forums. Such long-term thinking is required to continue the emerging trend away from reactive management to proactive and strategic planning – particularly in how to respond to future natural disasters, and climate and environmental change.

Recommendation 4: Preserve and use what we know more effectively. Preserving institutional and community knowledge, relationships and collaborations as institutions evolve is vital. The institutional makeup of the industry has become more fragmented over time, but also now includes a much wider range of different institutions. However, as the structure and priorities of institutions keep changing, there is an inherent risk that much of the former knowledge is lost. The emerging trend of increasing collaboration between institutions is encouraging, but can only persist where institutions are reasonably stable, transparent and demonstrate good water governance[47].

Recommendation 5: Step-change industry influence on policy and implement large-scale stream management. The industry must improve its ability and capacity to influence legislation, policy and regulations that support a shift towards large-scale stream and catchment management. This requires application of socially and environmentally ethical, just and transparent decision making at all levels[48,49]. It also requires commitment to local, national, regional and global agreements and visions. Feedback from policy-makers to the industry is important, to reflect on lessons from past advances and failures, and to improve understanding of the policy cycle among practitioners, researchers and the community. We demonstrated some successes with a relatively rapid transition of ideas from science to policy to adoption (e.g., flood management, environmental flows). This leads us to be confident that incorporating the vision and aspirations of the UN goals directly into policy and legislation would likely lead to their successful implementation.

Methods

Conference proceedings as a data source. This analysis was based on interrogating the proceedings of the Australian Stream Management (ASM) conference over its 25-year history from 1996–2021. Conference proceedings are an important repository of scientific knowledge and practical application, occasionally bridging the divide between research and practice. They are often interrogated as part of systematic reviews[50], including those which take advantage of them as a time-series of work in a discipline. For example, Snelson and Talar[51] used content analysis to investigate if the scientific quality of papers in their discipline improved with time, whilst Garner, et al[52]. simply explored the popularity of different topics over time. Casas-Mulet, et al[30]. used topic modelling across 11 eco-hydraulics conferences to track more complex trends, such as whether papers were becoming more interdisciplinary over time. While papers published in proceedings tend to have less scientific impact than those in journals[53] we believe that they provide more insights into a discipline area and industry than a review of the formal indexed literature. Many people publish in proceedings who do not publish in journals, including community members and policy-makers, providing a richer cross-section of a discipline.

The ASM conference proceedings dataset. The ASM conference brings together a community of practice in integrated stream and catchment management, mainly from south-eastern Australia. Scientific and non-scientific contributions are encouraged, including feedback from policy-making and implementation, adaptive management cycles and community participation. Compared to journals on the same topic, the ASM proceedings better reflect how stream management is being done in practice, and how knowledge is being shared.

Over its history, the conference has had a consistent format, with most content provided by contributed papers, and a handful of invited papers or keynotes each conference. Almost all contributors write full papers 6-8 pages in length, with a consistent template that has been maintained for 25 years, while a few contribute abstracts or extended abstracts. The proceedings are therefore a rich source of information over time about what is being done and what is being communicated (and by whom) in Australian stream management. The first six ASM proceedings were previously analysed for disciplinary areas, interdisciplinarity and evidence of adaptive management[13]. The present analysis provides a more robust exploration of author demographics, collaboration patterns, topics and interdisciplinarity, using a combination of metadata review, structured expert review and automated topic modelling. It tests specific hypotheses related to the advances in stream management that are needed to support the UN SDGs. It also reveals patterns over a longer timescale (25 years compared to 15), allowing us to assess long-term trends and evolution of topic areas over that time.

Other conferences in Australia cover aspects of stream management but tend to focus on narrower sub-topics or broader themes that only partly intersect with stream management, e.g., those focusing on freshwater science, the water industry, or stormwater management. Every conference has biases arising from geographic location, disciplinary and philosophical focus. The ASM proceedings dataset that we use may be influenced by such biases but avoids other biases that would be present in other conference or journal datasets.

The ASM conference has always been dominated by attendees and authors from Victoria, New South Wales, and Queensland, which are also the most populous states (containing 77% of Australia's population) and where most of the stream management industry is based. Victoria, which contains 25% of Australia's population, tends to be somewhat overrepresented, with 37% of all papers having a first author from Victoria. Australian Capital Territory is also overrepresented with respect to population, reflecting the concentration of river management organisations in the nation's capital. Western Australia, where the conference has never been held, is severely under-represented (1% of first authors from 11% of population) and has become more so over time, suggesting a separation of the Western Australian industry from that of the south-eastern States.

Rural and regional areas are well-represented. For example, delegate data for 9ASM (see Supplementary Table 2) revealed that for Victoria, 33% of delegates were from rural or regional areas, compared to 25% of the total population. Rural and regional representation was even higher for New South Wales. It is perhaps natural that the stream management industry is slightly more distributed across the landscape than the general population, providing greater geographic coverage of areas where rivers and streams exist. It is likely, however, that Aboriginal and Torres Strait Islander peoples are under-represented in the conference authorship and attendance, given that Victoria is overrepresented yet contains only 8% of Australia's Aboriginal and Torres Strait Islander population.

The location of conferences appears to have an influence on the distribution of attendees and authors, but this effect is inconsistent. For example, the representation of South Australian, Tasmanian and Queensland authors showed appreciable peaks when the conference was held in those states, while the representation of Victorian authors was highest in New South Wales in 2016. 10ASM, which was planned to be a hybrid format and might therefore be expected to have less bias associated with conference location, had similar distributions of authors to earlier conferences (see Supplementary Table 1).

Each conference from 1999 to 2016 had a theme and some of the more specific themes likely had some influence on submission topics and the vocabulary used in papers, which may have skewed the results of our analyses for particular conferences. However, conference themes were specifically selected as they were topical within the industry at the time. It is therefore difficult to assign causality for shifts in the topic focus or vocabulary of papers to conference themes. For example, the theme in 2012, which came after several years of the industry needing to respond to major drought, fires and floods, was 'managing for extremes'. Additionally, the analysis was focused on longer term trends across all conferences, which are likely minimally influenced by any anomalous shifts associated with the themes of individual conferences. Further, most of the themes were general in nature (e.g., 'Australian rivers: making a difference' (2007); 'twenty years on' (2016)), and the final two conferences had no theme, following a recognition by the organising committee that themes had little function or value in shaping the conference.

The philosophical focus of the conference leans towards pragmatic management applications rather than theoretical advances[13]. Papers tend to highlight novel and important advances in management, or theory that is ready to influence management. Other, more academic conferences and journals may include more theoretical and scientific advances but it is unclear how many of those advances go on to influence practice and what the time lag is. By interrogating proceedings which focus on the boundary between theory and practice we are able to interpret the evolution of the industry itself. Moreover, the ASM proceedings provide an immense opportunity to do so, given that such a rich and consistent set of full-text papers have been archived over 25 years. Such an opportunity does not exist at conferences where only abstracts are archived.

The ASM proceedings are therefore reasonably representative of advances in the stream management industry of south-eastern Australia, and can be used to infer evolution of the industry. The patterns we observe in south-eastern Australia may be more or less representative of other locations (likely more representative in countries which are more culturally, institutionally and geographically similar to Australia). Nonetheless, this analysis of one geographically-defined area can be used as a model for other similar analyses where long-term text datasets can be found that reflect the industry.

Structured review of proceedings. We undertook a structured review of all papers and abstracts ($n = 958$) across the ten ASM conferences. Our analysis catalogued the demographics of authors (gender, institution type and location) and their collaboration networks. We also assessed whether papers documented adaptive management practices (building on the dataset developed by Fryirs et al.[13] of 1ASM to 6ASM) or policy-related content. The new data were collected by nine annotators, each of whom was assigned a portion of each conference's proceedings to reduce the likelihood of inter-annotator variability in subjective categories affecting trends. We recorded the number of authors, their gender balance, affiliation categories (e.g., consultant, research, government/utility, NGO/community) and locations (state/international). Author diversity is an indicator of collaboration quality[54], and gender, institutional and location diversity were the only dimensions of diversity we could assess from the available information. We recorded whether the paper was a cross-institutional, interstate, or international collaboration. We noted whether each paper documented rehabilitation success/failure (as an indicator of adaptive management), knowledge-based policy advances or policy failings/limitations.

To explore overall trends, linear regressions were fitted between each response variable and year, and the strength of the relationship was assessed. For interpretation of p values, the standard alpha level of 0.05 was corrected using the Benjamini-Hochberg procedure[55] to reduce the chance of false discoveries being reported in this study. Correcting the alpha level for 78 tests across the whole study (i.e., 14 tests from the structured review, plus trend detection of topic prevalence for $K = 60$ topics, plus 4 derived indicators from the topic modelling) resulted in a significance threshold of 0.01. Trends with $p < 0.01$ were therefore considered statistically significant while models with $0.05 < p < 0.01$ were supported by weak evidence only.

Collaboration network graphs were developed for 1996 and 2021. Nodes represented nine author institution types (consultant, university, research institute, federal government, state government, local government, catchment management group, utility, NGO/community). Edges represented coauthorship between each pair of institution types (36 edges in total). Node size was scaled by the proportion of papers with that institution type represented as an author affiliation. Edge width was scaled by the proportion of papers with that pair of institution types collaborating on authorship.

Review of delegate data. Delegate lists for 1ASM, 9ASM and 10ASM were digitised and gender, affiliation institution type and affiliation location were summarised. Summaries were generated for all delegates, delegates who were authors and delegates who were first authors. The results were interrogated to indicate biases between the set of authors and attendees, and which sectors of attendees were over or under-represented as authors.

Topic modelling. Unsupervised topic modelling was undertaken to detect themes in the proceedings. Topic modelling using Latent Dirichlet Allocation (LDA)[56] is well-established in the field of Natural Language Processing (NLP), and has been applied widely to detect topics in journal articles, including in environmental management fields (e.g., ecohydraulics[30]). LDA is a method to determine a set number K topics in a set of documents. Under the LDA data model, each topic contains a mixture of words and each document contains a mixture of topics. LDA is a bag-of-words model where word order is not important. Subsequent advances in topic modelling include Correlated Topic Modelling[57] (CTM) which includes correlations between topics and is able to better model scientific disciplines in large document collections than LDA[58]. Structural topic models[59] (STM) introduce covariate information into the model, allowing metadata about each text (e.g., time, author attributes) to influence topic prevalence (the proportion of a document devoted to a topic) and topic content (the rates of word usage in each topic). STM is therefore particularly useful in the social sciences where inferences need to be made about what influences text content. STM has been found to outperform LDA and other state-of-the-art topic models on open-ended survey responses[59] and collections of news articles[60], and has been applied to collections of scientific and social science literature[61,62] to understand dominant research topics and emerging trends.

The machine learning library GROBID (2018–2021) was used to extract body-text from PDFs of individual papers. Abstract-only documents (those with less than 300 words) were excluded ($n = 26$) following Syed and Spruit[63], leaving a corpus of 932 body-text documents. Spell-checking (using 'hunspell' in R) revealed that two documents had more than 10% unrecognised words. One of these had correct but highly technical language and the other had many optical-character-recognition (OCR) errors that couldn't be fixed, totalling 14% of words. Both documents were retained in the corpus. Punctuation, special characters, digits and 175 common English stopwords (based on the 'snowball' list in R 'stopwords' package) were removed. Words were kept whole, without stemming or lemmatisation, following the findings of Schofield and Mimno[64]. Uncommon words appearing in less than five documents were removed to optimise performance and enable reliable trend detection, as per Casas-Mulet, et al[30].

The structural topic model[59] (STM) was used, to take advantage of its ability to model metadata effects (in this case, to detect trends over time). The 'stm' R package v1.3.6 was used to fit models across multiple K values (10–100) using spectral initialisation and including year of publication as a topic prevalence covariate. No topic content covariate was included. Model diagnostics including held-out likelihood, semantic coherence and exclusivity were inspected to guide the selection of K. $K = 60$ was selected as the final number of topics based on manual inspection of top-word lists to assess which model had the most interpretable and useful set of topics for our analysis.

Topics were labelled manually, grouped into broad disciplines (abiotic science, biotic science, integrative science, community participation, and management and policy), and flagged according to their ability to answer specific study questions. Flags were based on whether the topic related to adaptive management or the policy cycle. For each discipline and flag, prevalence of all topics with that discipline or flag was aggregated (i.e., summed) for each paper. Top-word lists, labels and flags for each topic are presented in Supplementary Table 3, and reproducible code and data are available for this study. Topics that were of special interest as aligning with identified natural or policy events or expected trends were identified for closer examination, as detailed in the Results and discussion.

Interdisciplinarity was indicated by two measures. Papers were identified as cross-disciplinary (integrating biotic and abiotic sciences) where they either had (i) prevalence >0.1 for a topic categorised as integrative science; or (ii) prevalence >0.1 for a topic categorised as abiotic science *and* prevalence >0.1 for a topic categorised as biotic science. Papers were identified as transdisciplinary (integrating science and management/policy or community participation) where they had prevalence >0.1 for a topic categorised as abiotic science, biotic science, or integrative science *and* prevalence >0.1 for a topic categorised as community participation or management and policy.

Coefficients of the modelled STM relationship between topic prevalence and year were inspected along with their p values to identify trends in topics over the whole period. Unstandardised coefficients (b) were used as they are more interpretable (b is simply the change in prevalence per year) and all coefficients are on the same scale and therefore comparable. As per the structured review, trends with $p < 0.01$ were considered statistically significant while models with $0.05 < p < 0.01$ were supported by weak evidence and would require further data to confirm whether a trend exists. Non-linear changes over time (e.g., spikes or dips) were assessed qualitatively against the policy and natural event context in the preceding period, to gain insight into drivers of rapid topic change.

Topic associations within documents were explored using cosine similarity of vectors containing the prevalence of each topic within a document. The matrix of topic prevalence and documents was split into the ten conference years, and a cosine similarity matrix was constructed for each year. For interpretability, only the 20 most prevalent topics for each conference were included in the analysis, to provide insight into associations between major topics. For each pair among the 20 most prevalent topics, the cosine similarity was calculated between the two vectors of topic prevalence by document. Network graphs were constructed to illustrate topic similarities over time, with edge width scaled by similarity and node diameter scaled by prevalence. Similarities <0.1 were excluded from the analysis.

Possible sources of bias in topic modelling include distinctive vocabulary of individual authors[65], or changing vocabulary over time, unrelated to underlying topics. We inspected topic word lists (Supplementary Table 3) for overly specific vocabulary. For example, several topics contained place names along with specific vocabulary which may indicate the study or application of certain topics tends to align with particular locations. Where the vocabulary was otherwise coherent and a topic could be easily assigned independent of the location, it was interpreted as a meaningful part of the industry. For example, topic 10 (sediment budgets) comprised words used by a subset of authors writing about sediment in the Great Barrier Reef catchment (e.g., GBR, gully, SedNet, reef, Burdekin) but was clearly a meaningful topic, the sharing of which helps to build capability within the industry in both sediment studies in general and protecting the reef specifically. Conversely, topics 17 and 21 contained place names and general management-related words which were difficult to label as topics. We minimised biases in the human-constructed topic labels, disciplines, and categorisations through an annotation process whereby multiple expert annotators checked and discussed labels before the final set was constructed. Topics that generated more discussion or disagreement tended to be those labelled under the management and policy discipline (e.g., topics 16, 17, 21). These topics were not otherwise used for interpretation.

Data availability

All data needed to reproduce results, figures and tables (including structured review data, delegate data and topic model results) is available at https://osf.io/ybkur/.

Code availability

R code for topic modelling, trend detection and reproduction of figures is available at https://osf.io/ybkur/. Code was run using R version 4.1.1 and the R packages hunspell 3.0.1, stopwords 2.2, tm 0.7–8, stm 1.3.6, tidyverse 1.3.1, igraph 1.2.7, readxl 1.3.1, grid 4.1.1, and gridExtra 2.3.

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