



REVIEW

Citizen science contributions to environmental risks assessment and management: A systematic map and qualitative evidence synthesis

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Abstract In an era of systemic risks from natural and human-induced hazards, we need approaches that address such risks at different governance levels, including those at the community level. Citizen science (CS)—public participation in research—is one such approach that has the potential to benefit risk assessment and management. Building on systematic evidence synthesis methodologies, we examine the individual and collective benefits from CS to environmental risk assessment and management. From systematic search results (9277 records), we found 133 publications dealing with the topic in-depth. Results show that CS is increasingly being recognised for risk assessment and management and several individual-level benefits (e.g., improved scientific skills) support outcomes for communities (e.g., increased community capacity). Identified knowledge gaps include (i) unidentified potential of CS for different risk governance phases, and (ii) scattered evidence of CS community outcomes in different geographic regions. We conclude that CS can increase resilience amongst vulnerable communities.

Keywords Citizen science · Environmental risk · Outcomes · Participation · Risk governance · Systematic map

INTRODUCTION

Natural hazards (e.g., floods, droughts, wildfires) often intertwine with human-induced hazards (e.g., pollution,

biodiversity loss or water scarcity), resulting in systemic risks (Trenberth 2018). These risks lead to vulnerabilities, cascading effects and tipping points within and across systems (Hochrainer–Stigler et al. 2024). Typical examples are climate related risks, where greenhouse gas emissions contribute to climate extremes, causing critical infrastructure damage (ibid.). As environmental risks can threaten the human wellbeing or survival as well as ecosystems, addressing them is vital. The International Risk Governance Council (IRGC) (IRGC 2019) and the UN Office for Disaster Risk Management highlight risk assessments and management as two essential tools for minimising and managing harmful effects, but also for increasing affected communities and stakeholders’ resilience (UNDRR 2017). The UN’s strategy for Disaster Reduction (United Nations 2011) and UN framework for risk management (UNDRR 2017), emphasise the importance of community-based risk management approaches, via e.g., knowledge transfer, community capacity, and community participation. Additionally, the IPCC (Intergovernmental Panel on Climate Change) notes that while local people deal with climate risks (by proactive behaviours and protective actions), local community resilience needs to be built to empower local decision-making to manage climate extremes (Cutter et al. 2012). The latest IPCC report highlights effective adaptation to climate change risks (e.g., sea-level rise) are best underpinned by inclusive community involvement (IPCC 2023). The work done by governmental institutions alone is not sufficient to tackle the impacts of systemic risks—much more widescale and concerted efforts by including the public and local people are needed to build resilience to risks. Involving citizens in citizen science projects to assess and monitor risk is one way of achieving this.

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Citizen science (CS)—public involvement in scientific research—has risen exponentially globally in recent decades (Berti Suman and Alblas 2023). The number of scientific publications reporting research using the term “citizen science” in the Web of Science (WoS) platform rose from less than 10 publications in 1995, when the term was coined (Kullenberg and Kasperowski 2016), to around 1281 in 2024 (topic searches, i.e. title, abstract, keywords, done by the authors in August 2025). CS is largely practiced in biodiversity- or geography-related studies, but other disciplines (e.g., medicine or public administration) are also beginning to recognise the CS potential. For example, a study mapping 503 environmental EU-based CS projects, found almost 70% involved biodiversity and landscape management, whereas air and water quality comprised 7% and 6% respectively; however, environmental risks covered only 1% of the sample (Turbé et al. 2019).

The literature shows that CS is expected to fulfil different goals, such as contribute to research outputs, democratise science, provide learning opportunities for participants, and support environmental policy (Turbé et al. 2019). In the environmental domain, CS may help to gather large-scale data and data from hard-to-reach areas (e.g., distant from urban centres) (Crain et al. 2014). The learning benefits of CS are well-documented, for instance, CS can increase environmental awareness and direct people to appreciate nature more (Ganzevoort and van den Born 2019; Peter et al. 2019). CS can also provide inputs to policy, by helping to identify the problems, contribute to the implementation of policies, and monitor the implementation outcomes (Turbé et al. 2019). For example, CS is already contributing to the monitoring of 33% of the 231 indicators of SDGs (Fraisl et al. 2022).

Despite the many benefits of CS, drawbacks also exist. Perhaps the most mentioned critique includes issues of CS data quality, arising from e.g., in inadequate adherence to data collection procedures by the volunteers, or volunteers’ training levels being unfit for the purpose of specific initiatives (Balázs et al. 2021). In practice, CS projects may not always fulfil all participants’ expectations, because they pursue one specific goal (e.g., advancing research), which may also leave some participants disappointed. CS requires skills, from project organisers as well as from the volunteers: poorly managed CS projects may demotivate volunteers and inhibit their future participation (Fraisl et al. 2022). Also, although CS is expected to democratise scientific research, it might exclude certain marginalised or underrepresented groups which may also call into question the usefulness of CS for those groups (Fraisl et al. 2022; Berti Suman and Alblas 2023).

Risk management public participation has explicitly existed from the 1990s (Fiorino 1990). The benefits include

increased legitimacy; problem ownership; a collective understanding of how to interpret the situation; and of a design process leading to acceptable collective binding decisions (Renn et al. 2011). Yet, CS as a form of evidence-based public participation in risk research and management has only recently been sporadically recognised in risk governance literature. For instance, CS is mentioned as a mechanism to report natural hazards (e.g., landslides, earthquakes) but active hazard reporting and their impacts is underutilised (Ward et al. 2020), pointing to a research gap. Also, behavioural elements (e.g., increased awareness, community preparedness) are seldom regarded as inherent risk management components (ibid.).

There is a strong call for the practical assessment and CS evaluation in research projects (e.g., von Gönner et al. 2023). Existing reviews show that CS impact has been studied foremost as individual learning gains (Peter et al. 2019, 2021; Somerwill and Wehn 2022), however, studies on the larger-scale CS outcomes have remained scarce (von Gönner et al. 2023). Outcomes beyond the individual level include, for example, the impact on local communities (Wehn et al. 2021) but only a few meta-studies have touched upon CS outcomes for communities (e.g. Stepenuck and Green 2015; Groulx et al. 2017; Suškevičs et al. 2024). Related reviews intersecting with the environmental risks’ domain have been done on CS and environmental monitoring (e.g., Rathnayake et al. 2020), for instance, CS and water quality monitoring (Nath and Kirschke 2023). Yet, meta-studies focusing on environmental risks in relation to CS are still scarce (Marchezini et al. 2018; Hognogi et al. 2023). We provide a systematic map and qualitative evidence synthesis, using the framework synthesis method (Brunton et al. 2020), to identify the CS outcomes on the individuals and communities involved within the empirical scientific literature scope of environmental risks. We ask the following research questions:

1. What are the individual and community outcomes of environmental risk-related CS?
2. Do the outcomes differ when citizens participate via different CS engagement models?
3. What are the results implications for the environmental risk assessment and management design?

The analytical framework which has guided our review is outlined (“Analytical framework” section), before introducing the systematic literature search methods, selection and analysis (“Data and methods” section). After presenting the results (“Results” section) and the identified knowledge gaps, future research directions are discussed and implications for environmental risk assessment and management (“Discussion” section). In “Conclusions” section summarises our conclusions.

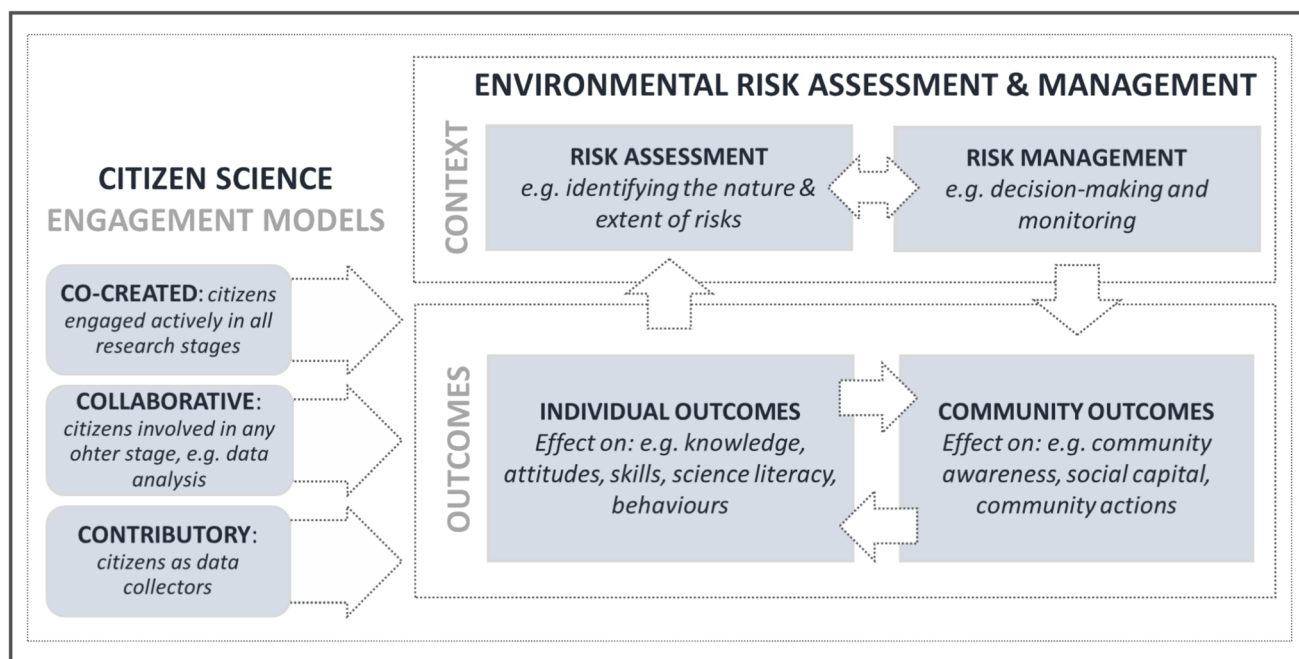


Fig. 1 Analytical framework (Source: the authors)

ANALYTICAL FRAMEWORK

We start out by defining an analytical framework which enables us to assess how different **CS engagement models** (left-hand side of Fig. 1) affect CS **outcomes**, i.e., support individuals or communities (bottom of Fig. 1), in the environmental risk assessment and management **context** (upper part of Fig. 1). We focus on outcomes, rather than ‘impacts’, which typically refer to large-scale, e.g., societal, and long-term effects. We understand outcomes as benefits or changes resulting from participating in CS projects for individuals and communities (Wehn et al. 2021). **Community** is defined as “group of people subjected to common risks or threat /.../ and with the capacity to recognize disruptive events” (Sharma et al. 2022). Although individual level CS outcomes have been studied in several reviews (Peter et al. 2019, 2021), our synthesis assesses individual outcomes as essential building blocks for achieving any larger-scale outcomes, such as community outcomes (Adamou et al. 2021). The next sections comprise of the analytical framework components.

Level of citizen involvement: Citizen Science engagement models

CS projects differ in the extent they involve citizen scientists in various stages of research. One of the most typically used typologies to distinguish between CS engagement models (Bonney et al. 2009), indicate the different degrees of citizen involvement in a CS initiative,

from the lowest level where citizens contribute data (contributory CS) to the collaborative CS (citizens contribute to any further research step, e.g., data analysis) to the highest involvement model (co-created CS) where citizens may be able to define their own research initiative focus, design and implementation.

Outcome categories

We define seven individual outcome categories and four community outcome categories (Fig. 1). These categories synthesise the typical outcomes found in current literature (e.g., Crain et al. 2014; Stepenuck and Green 2015; Peter et al. 2019).

Individual outcomes

These refer to changes in knowledge (cognitive domain), attitudes (affective domain), interest (assignment of relevance) and motivation (goal-drivenness), self-efficacy (confidence in abilities), scientific skills and science literacy (abilities to understand and perform scientific procedures, e.g., data collection), and behavioural change (actions resulting from engagement in CS) (adapted from: Peter et al. 2019). CS projects may emphasise one or more learning outcomes, but ideally, outcomes act together synergistically e.g., interest in CS activities creates new content knowledge and scientific skills, that support appreciation towards the environment and motivation for further investigations, potentially leading to behavioural

changes. However, few reviews have addressed the links between these outcome types (e.g., knowledge and actions) (Groulx et al. 2017; Finger et al. 2023).

Community outcomes

These outcome types refer to community awareness (knowledge and action readiness), social capital (e.g., formal and informal human networks formed between individuals), community capacity (e.g., social capital amongst the wider community that can be leveraged to solve collective problems), and community actions (actions suggested or taken towards e.g., resilience) (Jordan et al. 2012). Like individual outcomes, different community outcomes combined might help to realise the full learning potential of CS: e.g., community awareness on environmental problems might strengthen the social networks and thus support the capacities of local communities to respond (i.e., act) to environmental crises better.

Context: Environmental risk assessment and management

Our synthesis context is environmental risk assessment and management, which the IRGC considers as two spheres required to reduce hazard impacts (Renn et al. 2011; Florin and Bürkler 2018; IRGC 2019). The assessment sphere refers to the knowledge generation processes, and the management sphere to decision-making phases.

Risk assessment

Risk assessment identifies the nature and extent of risks, via analysing potential hazards (i.e., sources of danger) and evaluating the exposure and vulnerability of individuals or communities (UNDRR 2017). Risk assessment typically divides into more concrete phases, including pre-assessment (e.g., problem framing, early warning), risk appraisal (e.g., hazard identification, concern assessment), and characterisation and evaluation (e.g., risk profiles, judging the tolerability and acceptability) (Renn et al. 2011; Florin and Bürkler 2018).

Risk management

Risk management is a step further: i.e., referring to risk reduction policies and strategies, to prevent new risks or reduce existing risks, contributing to strengthening resilience and loss reduction due to hazardous events (adapted from: Florin and Bürkler 2018). Risk management measures could be direct ones, i.e., targeted at the hazards, or indirect ones, i.e., targeted at increasing the resilience of individuals and communities (ibid.). Communication and

stakeholder engagement are cross-cutting themes here, intersecting with all four phases (ibid.). An extended list of all variables and their definitions used for this synthesis can be found in the codebook (Supplementary 3).

DATA AND METHODS

This study is based on systematic mapping (Collaboration for Environmental Evidence 2022) and framework synthesis methods (Brunton et al. 2020). The latter belong to the family of qualitative evidence synthesis (QES) approaches (Macura et al. 2019), which refer to the group of methods aiming to systematically synthesise qualitative evidence. The following steps were taken (Fig. 2): (1.1) setting up a search string and conducting the searches, (1.2) filtering the search results to remove duplicates, (2) article screening and selection at title and abstract (TI-AB) and full-text levels, (3) codebook development and data extraction; 4) analysis and synthesis of the extracted data.

Systematic searches

The first step was to compile a set of keywords into a suitable search string (i.e., a combination of keyword groups connected with Boolean operators). The initial keywords used (Supplementary 1) are broader than the risk assessment and management field, since this research is part of a larger project which explores the links between CS and environmental policy.

Two academic research platforms were used: Scopus and Web of Science. “CS: Theory & Practice” journal was initially manually searched, as it was only indexed in these platforms in 2021. Searches in the English language were done 10th February 2021, using TI-AB and keyword searches in the Scopus and WoS platforms, and in the “CS: Theory & Practice” journal website, as shown in Fig. 2 and Supplementary 1. The searches were then updated from the Web of Science on the 26th February 2025 (2957 new publications) and Scopus on the 4th March 2025 (4165 new publications).

No time or geographic restrictions were applied to the searches. However, due to practical considerations, restrictions by publication types were applied: articles, reviews and book chapters were included; while conference papers, books, editorials, and data papers were excluded. This entails certain evidence base limitations, discussed in detail below (“Limitations” section). The records were exported to EPPI Reviewer Web, software designed to facilitate systematic screening and coding (University of London 2023, version 4.14.1.0). After duplicates were removed, 9277 original unique records underwent screening.

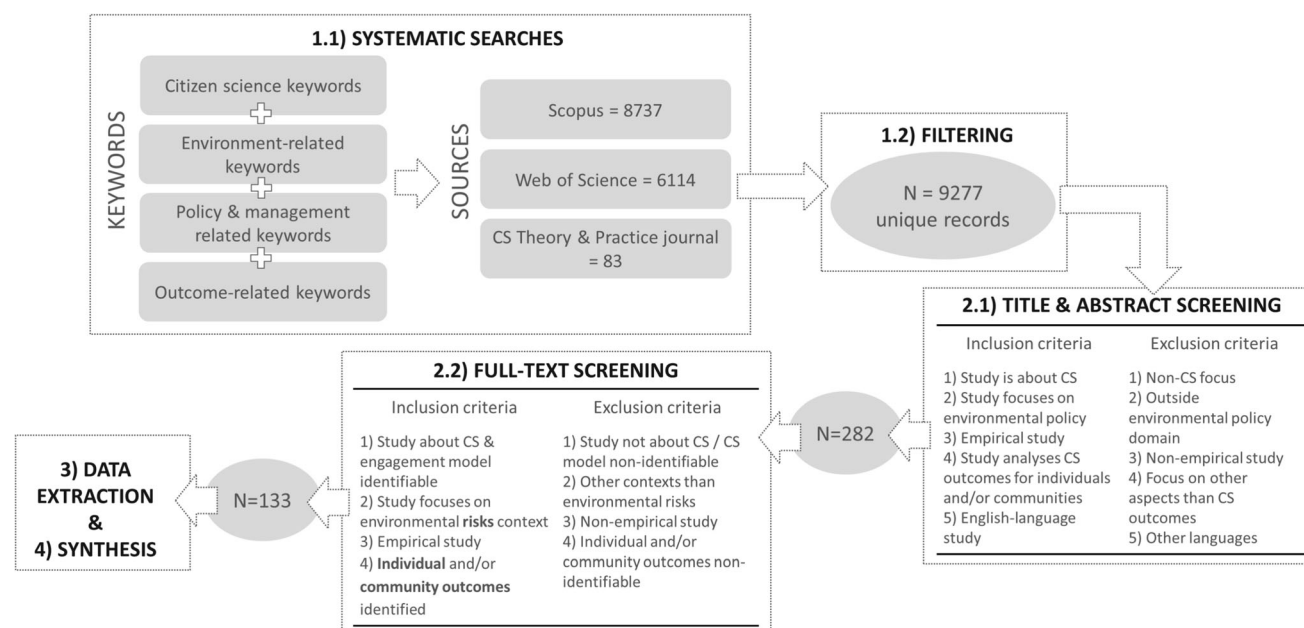


Fig. 2 Overview of the search and inclusion–exclusion process (Source: the authors)

Article screening

The 9277 search results were screened at two levels: (1) TI-AB level; and (2) full-text levels (Figs. 2 and 3). In the TI-AB screening level, we used the inclusion and exclusion criteria outlined in Fig. 2 (full criteria in Supplementary 2, Table S2.1). The criteria at TI-AB level were wider than environmental risks, because, as mentioned, this study is part of the larger project with the broader CS scope and environmental policy links.

TI-AB screening was done in two sub-steps. The first sub-step, i.e., an initial TI-AB screening resulted in 983 publications with indications of CS community outcomes. The second sub-step in TI-AB screening of the 983 publications' titles and abstracts, focused on environmental risks and applying the criteria outlined in Fig. 2. These sub-steps together resulted in a selection of 282 publications' full texts, with both indications of the environmental risks domain and CS community outcomes. These 282 full texts underwent further screening, according to the criteria outlined in Fig. 2 and Supplementary 2, Table S2.2. The whole publication selection process can be seen in Fig. 3. The final sample consisted of 133 publications (Supplementary 4) which had satisfied all screening criteria.

Data extraction, analysis and synthesis of the extracted information

We used framework synthesis (Brunton et al. 2020) for data analysis and synthesis. Framework synthesis is an evidence synthesis method where an analytical frame is generated from

the research question and existing literature (Fig. 1 above), against which the included studies are iteratively assessed as themes emerge from the data (Brunton et al. 2020). The framework synthesis method allows a structured and transparent synthesis of qualitative evidence (most our included studies, Table S5.1 in Supplementary 5), facilitating the presentation of the results for policy advice (ibid.). To extract data from the 133 publications, a codebook (Supplementary 3) was developed, containing the following themes:

1. Study description (e.g., publication year, journals, study location, risk types addressed),
2. Methods (e.g., study designs and data collection methods),
3. CS process description (e.g., CS participation models, terms referring to CS and citizen scientists),
4. Outcomes (i.e., individual outcomes and community outcomes).

For most coding items, deductive thematic coding was used, i.e. pre-defined concepts, such as behavioural change, interest, knowledge, motivation, self-efficacy and scientific skills and science literacy (Peter et al. 2019; Stepenuck and Green 2015). "Other individual outcomes" did not fit into the abovementioned pre-defined categories. Coded text was then synthesised by grouping together ideas from the selected publications. Similarities and differences were highlighted using tables and graphical charts and the findings summarised in a narrative synthesis that compared data patterns. The possibilities and barriers in the CS context and environmental risks management were further interpreted and explored.

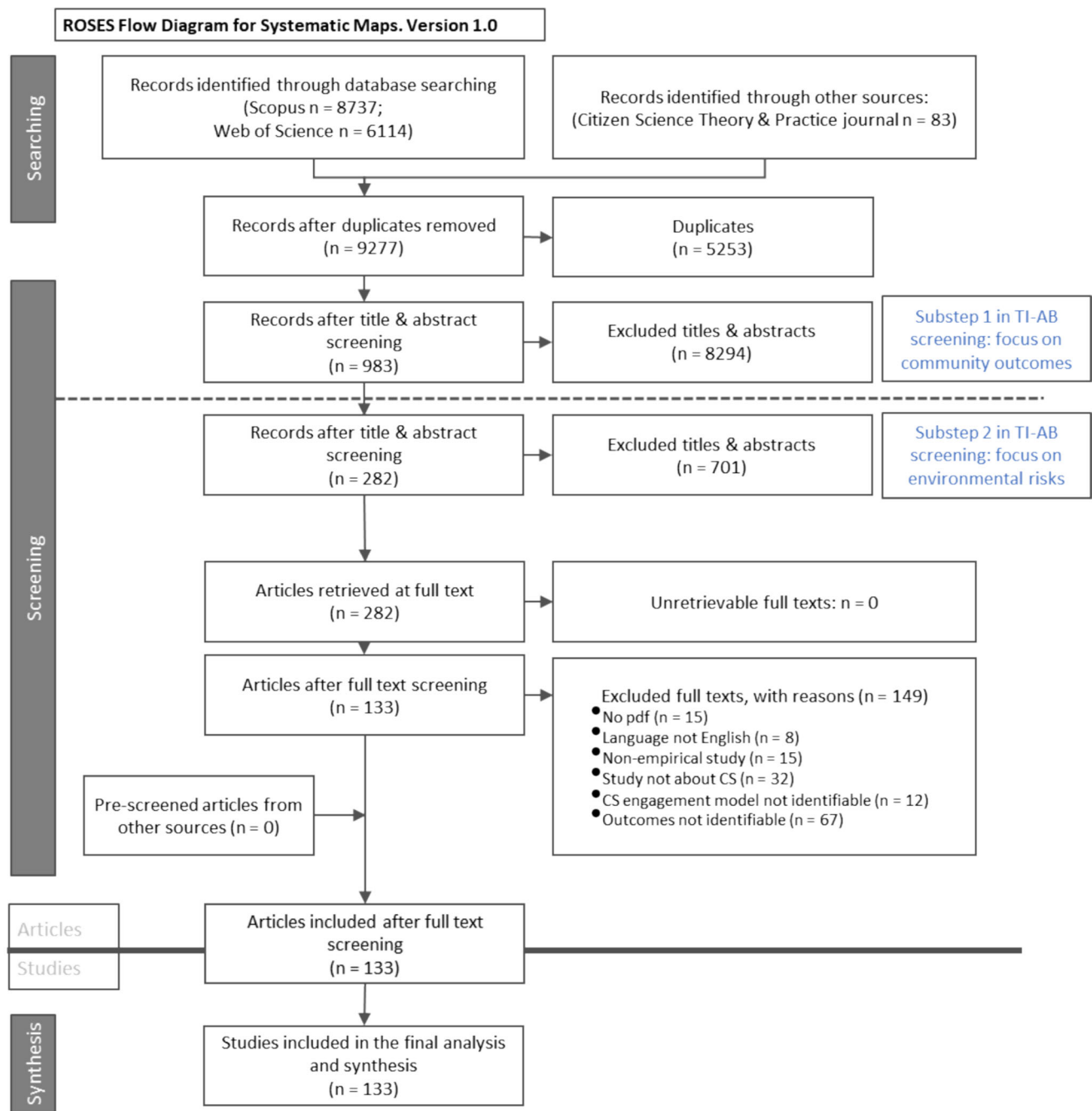


Fig. 3 Screening process flowchart according to RepOrting standards for Systematic Evidence Syntheses in environmental research (ROSES) (adapted from: Haddaway et al. 2018)

RESULTS

General elements in the selected articles

The included articles (n = 133, Supplementary 4) were published between 2012 and 2024 (Fig. 4A) in 92 journals (Fig. 4B). Their research was conducted at local and regional levels in 50 different countries (Fig. 5). Most

research was conducted in one country. However, six publications reported research conducted in multiple countries: nine countries across Europe, Africa, North and South America, and Australia (King et al. 2021), seven countries across Europe and North America (Johnson and Hendrikx 2021), two countries in Asia and Oceania (Wolff et al. 2021), the remaining publications covered five, two and four countries across Europe (Sirbu et al. 2015;

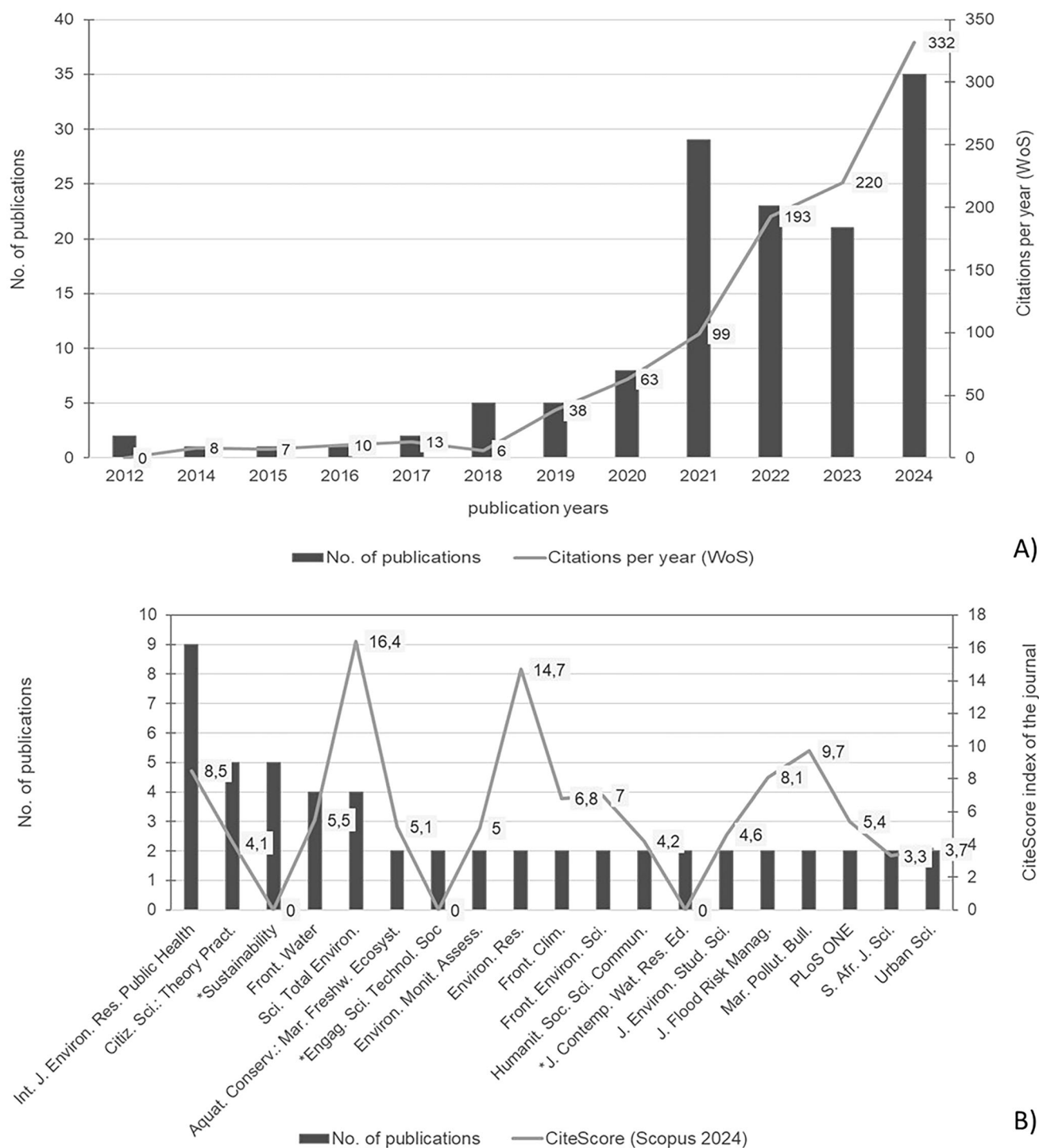


Fig. 4 **A** Publication years, **B** journals in which the included articles were published most frequently, i.e., at least two publications per journal (Source: the authors). See Supplementary 4 for the full journal list. Note *CiteScore info not available

Pudifoot et al. 2021; Froeling et al. 2024). The sample covered diverse thematic domains,¹ dominated by research

¹ Code groups for almost all codes are not mutually exclusive, except for CS engagement level where codings were not mutually exclusive in case of publications (6 articles) containing cases from multiple countries and employing multiple CS engagement levels.

on health risks ($n = 54$), water pollution ($n = 42$) and air pollution ($n = 29$) (Fig. 6). About half the publications ($n = 70$) addressed one risk, the rest ($n = 63$) addressed compound risks, e.g., air pollution coupled with health risks. Risk governance phases mainly covered the appraisal ($n = 106$) and management stage ($n = 115$), less the pre-

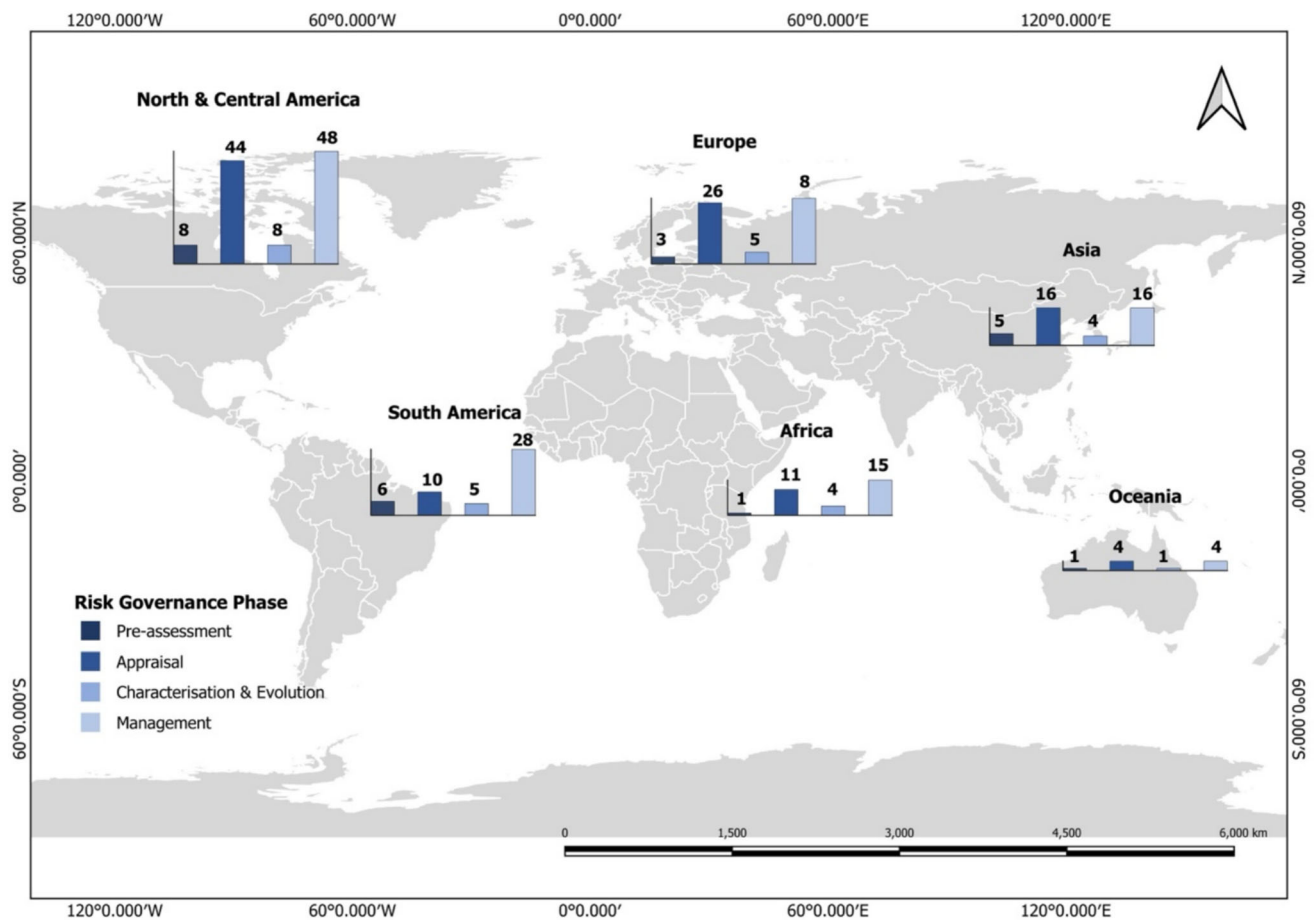


Fig. 5 Geographical representation of the studies and risk governance phases addressed in the analysed publications (map prepared by Ruthi Veibiakkim)

assessment ($n = 22$) and risk characterisation stage ($n = 25$) (Fig. 5).

In the reviewed articles, the citizen participation model most used was the contributory model ($n = 61$), while others employed the collaborative model ($n = 38$) or co-created model ($n = 28$). Due to multiple cases addressed in one publication, six articles indicated two models combined: contributory and collaborative CS (Supplementary 5). The reviewed articles used various terms to refer to CS, the majority being citizen science ($n = 111$), community science or community research ($n = 25$), and participatory science or research ($n = 19$). Participants came from diverse backgrounds, cultures, ages, gender, and different educational levels from highly educated individuals to those with little or no formal education.

The included articles employed different study designs and data collection methods to assess the outcomes: many used case study design ($n = 29$) but action research ($n = 15$) was also employed (Supplementary 5). Approximately half studies included designed their own CS

projects and assessed the outcomes, however, many studies assessed the outcomes from external CS projects (i.e., projects not initiated and conducted by the study authors). Multiple articles combined the CS projects with environmental education programs ($n = 34$). Assessments were typically based on post-participation responses or observations gathered throughout the process; however, some articles (particularly applying to environmental education programs) obtained pre- and post-participation responses ($n = 19$). No articles compared changes that occurred to a non-participant group.

Participant's learning outcomes

In our sample, 103 articles (77%) reported outcomes gained by individuals participating in research and action activities (Fig. 7A). These included cases where participants learnt scientific concepts by working on real projects: e.g., mapping landslides (Cieslik et al. 2019) or volcanic hazards (Joseph et al. 2019). The most common individual

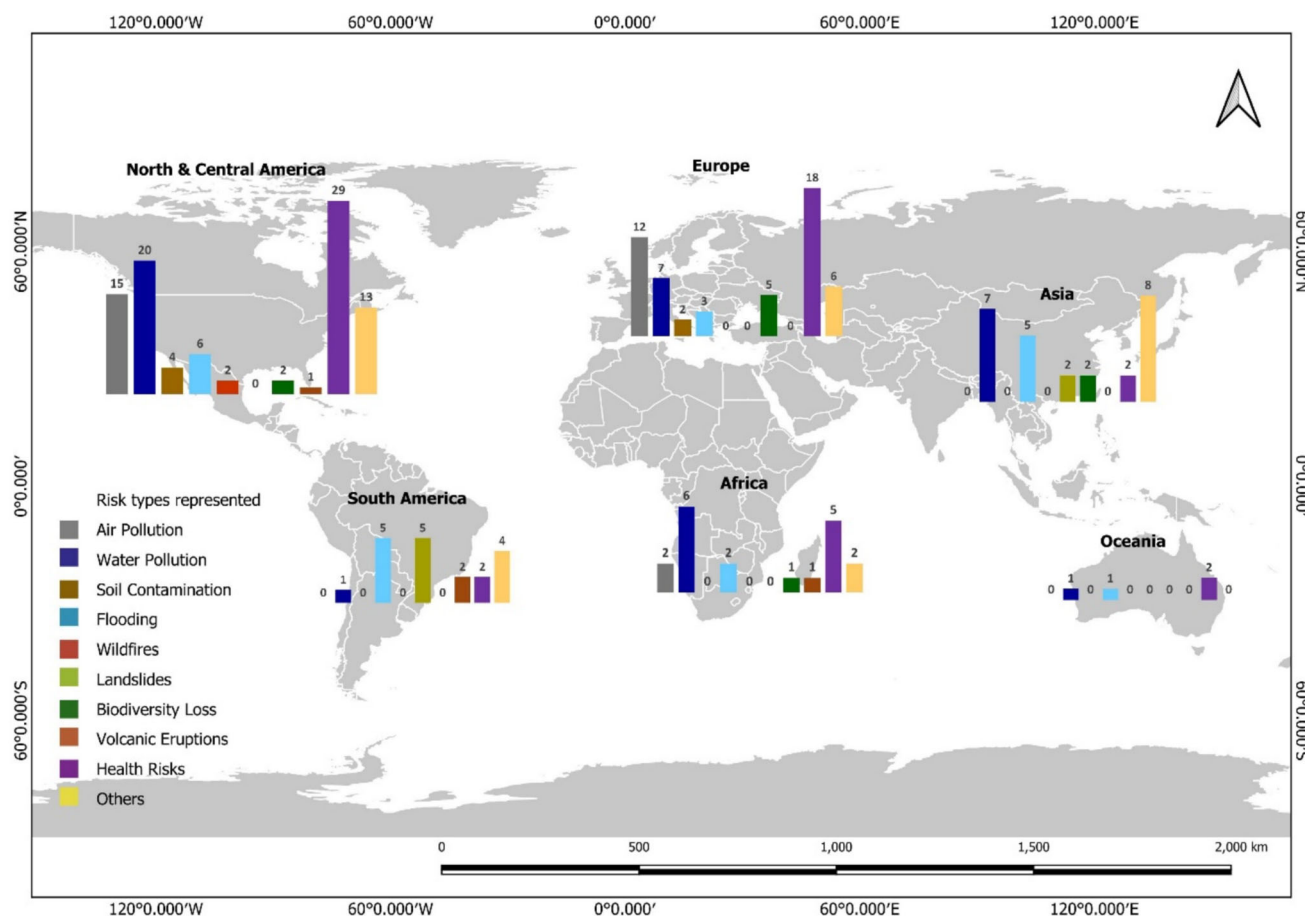


Fig. 6 Risk types represented in the sample (map prepared by Ruthi Veibiakkim)

outcome was participant's knowledge gained ($n = 77$ publications), followed by increased scientific skills and science literacy ($n = 47$), motivation ($n = 40$) and interest ($n = 38$). Behavioural change was mentioned in 30 articles. Participant's modified attitudes ($n = 22$) and self-efficacy engaging in the study's activities ($n = 16$) were the least commonly identified outcomes. Eighteen articles identified "other individual outcomes" (e.g., a choice to continue disseminating risk information after the programme's completion) and 30 articles did not mention any individual outcomes. The study now considers individual outcome types in detail, starting from the most frequently identified outcome types.

Knowledge gain

An increase in knowledge resulting from CS activities ($n = 77$) was often general content knowledge on the environmental issue studied. However, in many publications ($n = 20$) the knowledge was more complex, e.g., an understanding of the cause-and-effect relationships in the environment as well as hazards and their impact on the

humans (e.g., via exposure) (Hahn et al. 2020; Hultquist and Cervone 2018). Several publications (at least 7) refer to the knowledge usability, mostly in health-related risks (e.g., Durkin et al. 2020; Raheja et al. 2022) but also in other contexts. For instance, science teachers participating in ambient SO_2 concentration measurements to identify areas of elevated concentrations translated their knowledge into a teaching tool (Joseph et al. 2019). Further indication of knowledge gained was seen from gathering locally relevant knowledge ($n = 4$) (e.g., Froeling et al. 2024), gathering of new ideas (e.g., Anyolitho et al. 2024) and social learning ($n = 4$) (e.g., Da Schio 2022).

Scientific skills and science literacy

Citizen scientists attributed their increased science literacy, acquisition and/or improvement of new or existing scientific skills to their CS participation ($n = 47$). Some articles ($n = 12$) mentioned science literacy in general but many other also specified the skills' content. Some publications ($n = 19$) documented skills learnt during the scientific inquiry phases, including basic skills, e.g., observing,

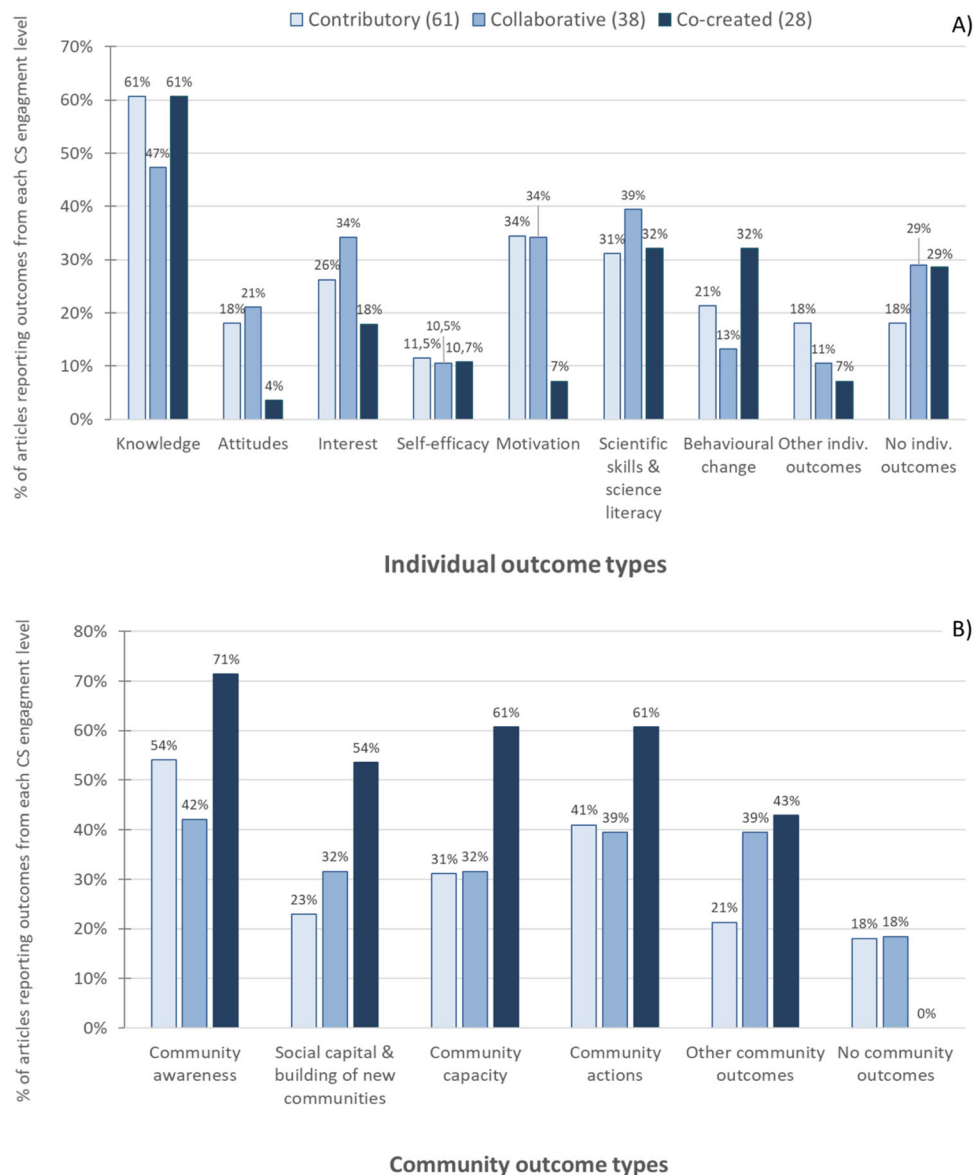


Fig. 7 **A** Reported individual outcomes, and **B** community outcomes across three CS engagement models, $n = 127$ publications (Source: the authors). Codes for CS engagement levels are mutually exclusive, the outcome codes are not. The six combined CS model articles are omitted from the sample for this graph, as it would not have allowed outcome type comparison with CS engagement models

questioning, site selection, but also more advanced skills e.g., sample collection and analysis, operating monitoring equipment, result documentation, data interpretation, reporting, drawing conclusions, and/or presenting the results (e.g. Matz et al. 2017; Musavi et al. 2018; Durkin et al. 2020; Hahn et al. 2020) up to designing the whole enquiry process (e.g., Marchezini et al. 2017; Gebeshuber et al. 2024).

Motivation

Citizen scientists' feedback in 40 articles revealed several aspects resulting from CS participation in projects. Most

frequent motivational outcomes ranged from learning something new ($n = 11$), a concern and a sense of duty to reduce family and community risk ($n = 11$), to actively influencing environmental safety decision-making ($n = 6$). For instance, residents' frustration at state-funded health research that discredited their observations and complaints about natural gas plant pollution fuelled their decision to participate in research that acknowledged their concerns and involved them in the research process (Allen 2018). Students engaged in stormwater research highlighted Science, Technology, Engineering and Mathematics (STEM) learning, new experiences and interesting topics as important factors for participating (Musavi et al. 2018).

External rewards (e.g., acknowledgement, competition) were also mentioned in some publications ($n = 5$).

Interest

Interest outcome reported ($n = 38$) is closely related to the motivation outcome. Mostly, it meant curiosity and seeking information regarding the issue citizen scientists studied ($n = 17$), followed by a long-term willingness to contribute ($n = 5$) (e.g., expand the monitoring network, Durkin et al. 2020). Participants ranged from professionals with prior knowledge of the issue, interested in working voluntarily with the researchers, to lay people who participated based on the benefits gained. In several publications (explicitly at least $n = 10$), interest was also a precursor for actions, e.g., citizen scientists prepared to take proactive steps to recruit others to participate (Sîrbu et al. 2015; Musavi et al. 2018; Wong et al. 2020) and willingness to contribute to risk communication (Kar 2016).

Behaviour change

Behavioural changes ($n = 30$), in certain articles ($n = 11$) included concrete actions observed or self-reported, which meant, for instance, litter reducing behaviours (Locritani et al. 2019), changes in certain daily practices regarding stormwater (Musavi et al. 2018), or preventive actions to reduce risk exposure, based on air pollution data, e.g., closing windows when particulate matter sensor's readings are high (Matz et al. 2017). In the other articles ($n = 19$), the behavioural changes meant more generic behavioural changes, such as CS fostering health-enhancing behaviours (e.g., King et al. 2021) or avalanche education and CS associated with desirable (i.e., less risky) behaviours (Johnson and Hendriks 2021) as well as disseminating findings of a CS project and translating results into action (Ramírez-Andreotta et al. 2023).

Attitudinal changes

Attitudinal changes ($n = 22$) often included an increased positive attitude toward the study object or environment generally (e.g., Kar 2016; Marchezini et al. 2017; Hsu et al. 2018; Wong et al. 2020). Examples include an increased optimistic feeling about the control measures of invasive species (Colombari and Battisti 2023) or an increased concern about marine litter (Locritani et al. 2019). Some articles (e.g., Joseph et al. 2019; Cornwell et al. 2024) noted a more positive attitude towards science, for example, greater acceptance of the ways experiments are done (Chaabane et al. 2024). Often, such feelings were accompanied by a positive outlook by the participants, such as towards contributing to

environmental protection as well as readiness to act. For instance, changes included feedback such as “*I feel prepared to partake in more citizen science studies; how can I get more involved in the future?*” (Hahn et al. 2020: 6) or a positive anticipation of the CS events “*a majority of the students looked forward to collecting data and learning new skills*” (Musavi et al. 2018: 7).

Self-efficacy

Self-efficacy was identified ($n = 16$) primarily among young participants (ages 8–21) involved in CS projects that provided them with skills, capacity and confidence to translate knowledge into action (e.g., Werthmann et al. 2024). In many articles mentioning self-efficacy as an outcome, the participants were involved in additional CS phases other than just data collection: for example, being able to independently collect and prepare laboratory samples, interpret real-time data to make decisions, students conducting peer-to-peer training and presenting their data to stakeholders, recruiting others (adults) to participate in research, explaining project content to residents and installing monitoring sensors, providing interactive educational demonstrations and giving presentations at state and national science fairs (e.g., Marchezini et al. 2017; Musavi et al. 2018; Durkin et al. 2020).

Other individual outcomes

Eighteen articles reported other individual outcomes that did not fall under any previously mentioned categories in the CS literature: e.g., empowerment (Tedla et al. 2024), or sharing CS experiences outside the project and thereby recruiting new volunteers (Matz et al. 2017; Musavi et al. 2018; Da Schio 2022) or students communicating risk to their families, as well as other community members (Savva et al. 2024). Other examples mentioned included an increased sense of place (Eberhardt et al. 2022), sense of responsibility and active citizenship (Boniardi et al. 2023) and stewardship (Savva et al. 2024).

Community outcomes

In the sample, community outcomes were reported in 115 articles (86% of the 133 articles). Community awareness was the most prevalent ($n = 74$), followed by community actions ($n = 61$) and community capacity ($n = 53$). Increased social capital and other community outcomes (e.g., project sustainability and continued collaboration in other CS endeavours) were the least observed: $n = 44$ and $n = 41$ respectively, while 18 articles reported no community outcomes. In the next subsections, we will describe each community outcome type (Fig. 7B) in detail.

Community awareness

Community awareness ($n = 74$) was often (47 articles) linked to general awareness-building about the investigated environmental issue and associated risks (e.g. water, air or plastic pollution), but in some articles, it was more complex, e.g. a better understanding of causal risk relationships (Ramírez-Andreotta et al. 2023) or new ways of social domain thinking, such as rethinking interdependencies in communities (Goldin et al. 2023), social learning (Micheli et al. 2024) and future thinking ability (Mishra et al. 2023).

Community action

Community action ($n = 61$) was manifested by a willingness to effect change through taking action to address the environmental challenge either as a community or in collaboration with relevant official authorities or organisations. Examples include producing strategies and management plans to reduce exposure or risk impacts (7 articles, e.g., de Paula et al. 2025) or suggesting risk reduction measures or policies (8 articles, e.g., Mickelsson et al. 2024). A number of publications (25) dealt with bottom-up activities, such as advocating for change based on local concerns and challenging existing regulations (Allen 2018; Froeling et al. 2024); mobilising actions to tackle pollution (Anyolitho et al. 2024) or self-organising and facilitating response to reduce risk exposure and initiating early warning communication channels (Stone et al. 2014; Cieslik et al. 2019; Pérez-Arévalo et al. 2024). Certain articles (6) mentioned actions that went beyond the CS project: for instance, seeking further collaboration and funding options (Wong et al. 2020; Jovan et al. 2022; Collins et al. 2023).

Community capacity

An increase in the communities' readiness ($n = 53$) to act addressing environmental challenges was indicated by community empowerment (14 articles, e.g., Jovan et al. 2022; Piontkivska et al. 2024), sense of agency and advocacy, supporting self- or locally organised actions to respond to crises (10 articles, e.g., Stone et al. 2014; McCormick 2012; Brodie et al. 2023), capacity to collaborate (8 articles, e.g., Stone et al. 2014; Pereira et al. 2023), adaptation capacity and resilience (8 articles, e.g., Pérez-Arévalo et al. 2024), stewardship (5 articles, e.g., Da Schio 2022), as well as proposing implementable ideas beyond the concrete project (McCormick 2012; Pandeya et al. 2020; Collier-Oxandale et al. 2022).

Social capital and building new communities

44 articles reported this outcome, mostly new partnerships or networks built (17 articles, e.g., Durkin et al. 2020; Hadfield et al. 2024), strengthened existing relationships (13 articles, e.g., Allen 2018; Wong et al. 2020), trust-building (9 articles, e.g., Raheja et al. 2022; Werthmann et al. 2024), and collaborations fostered (6 articles) (e.g., Marchezini et al. 2017; Durkin et al. 2020; Pandeya et al. 2020; Nqowana et al. 2024). In one case, up and downstream communities were reconnected through the development of an early-warning flood system (Tedla et al. 2024) and in another case, the scientists acted as mediators to build trust (Stone et al. 2014).

Other community outcomes

Other community outcomes ($n = 41$) reflected more positive impacts geared towards communal benefits. Often ($n = 11$) power redistribution, democratisation of the knowledge co-production processes and community empowerment were referred to (e.g., Cardarelli et al. 2021). Several publications ($n = 8$) mentioned justice or equity (e.g., Jovan et al. 2022). In many articles, volunteers were also keen on ensuring the project's expansion and sustainability beyond the research's timeline ($n = 9$) (e.g., Hsu et al. 2018; Joseph et al. 2019; Wong et al. 2020; Collier-Oxandale et al. 2022). For instance, air monitoring programme participants suggested increasing the sensor numbers and identified further locations to facilitate informed air quality decisions beyond the immediate community project area (Musavi et al. 2018; Durkin et al. 2020).

Co-occurrences between the main variables

Individual and community outcomes. Slightly over half of the sample (85 articles, 64%) reported both, individual and community outcomes. Most of the co-occurring outcome groups included outcomes related to individual knowledge combined with any of the community outcomes (e.g., community awareness, capacity or actions) (see Supplementary 6). Individual skills and science literacy co-occurred also with several community outcomes, such as community awareness or capacity.

Individual/community outcomes and CS engagement levels. Individual outcomes are more evenly dispersed across the three CS engagement levels (Fig. 7) than community outcomes. Behavioural outcomes are slightly more represented in the co-created CS section, whereas scientific skills' outcome appear more in the collaborative CS subsample. All CS engagement levels had indications of community outcomes. Outcomes related to social capital

and community building in contributory CS are less common than in other CS models. Co-created CS articles seem to report community outcomes more frequently than contributory or collaborative CS (Fig. 7). Additionally, all papers in the co-created CS subsample reported some community outcomes.

DISCUSSION

Identified focal points, knowledge gaps and future research directions

Our systematic map enabled us to give an empirical literature overview where CS intersects with environmental risk research. The geographical distribution of the included articles (i.e., most studies from USA) broadly correlates with existing reviews (e.g., Stepenuck and Green 2015; Rathnayake et al. 2020). However, Europe is somewhat less represented in our sample than in the reviews cited above. Potential reasons might be the natural disaster distribution pattern (most in Asia, USA) (Statistica 2024), but also differences in the state institutions' capabilities for mitigating their impact.

The presence of systemic risks, surrounded by uncertainty, requires building resilience from below: a concept acknowledged in sustainability transformation debates (Scoones 2024). About half the publications in our sample addressed more than one risk type, indicating the issue of compound risks. Communication and stakeholder engagement are outlined as cross-cutting aspects in the IRGC risk governance framework (Renn et al. 2011; IRGC 2019). Reviews on CS show that systemic thinking knowledge and skills (e.g., argumentation, problem-solving skills) from CS projects are strongly related to collaborative skills and local scale actions to address environmental problems and promote community resilience (Adamou et al. 2021). However, raising awareness, skills and changing behavioural aspects are seldom regarded as risk management measures in the IRGC framework, pointing to a gap, and potential issues as only aspects that are considered important will be monitored. Additionally, CS rarely explicitly features in the risk governance literature, e.g., only sporadic mention of CS terms (Florin and Bürkler 2018). Thus, our study is a step towards bringing CS and risk governance literature into a closer dialogue. Except for certain journals (e.g., 'International Journal of Environmental Research and Public Health', $n = 9$ articles; 'Citizen Science: Theory and Practice' and 'Sustainability', both $n = 5$), the research sample has been published in diverse journals, mostly with a high impact factor (Fig. 4A), and interdisciplinary focus (i.e., listing more than one subject area) (Scimago Lab 2025). This indicates CS is still a new topic in the risk

research literature. Existing reviews demonstrate CS can contribute to early-warning systems (Marchezini et al. 2018), but early warning is only part of the full risk management cycle. The synthesis indicates CS is already contributing to several other phases, e.g., risk appraisal, or management (Fig. 5 and Supplementary 5). However, further investigations are needed, to demonstrate how specific risk assessment and management phases (e.g., risk characterisation) benefit from CS.

The CS participation models' distribution in our sample (i.e., mostly contributory CS) is typical in the CS literature, as simple forms of research with the citizens (i.e., contributory CS) are still the most common in the environmental CS domain (Vasiliades et al. 2021; Suškevičs et al. 2024). Although more specific and quantitative comparison of these three CS models and their outcomes is not feasible due to the small numbers of articles representing each CS engagement level (less than 100 each) in the whole sample, some tendencies are still visible. For instance, co-created and in some cases collaborative CS typically had fewer individual outcomes reported, but frequently more varied types of community outcomes than contributory CS. Conversely, the number of articles reporting no community outcomes was larger in contributory CS articles (11 articles) than in collaborative CS articles (7 article). It could be hypothesised co-created or collaborative CS forms may contribute more diverse outcomes (a tendency shown in similar reviews, e.g., (Suškevičs et al. 2024)), better fitted to respond to environmental risks. This requires further research which includes a more equal distribution of publications with different CS engagement levels, to enable comparisons.

Our results indicate that CS supports diverse outcomes, with community outcomes (115 publications) slightly more represented than individual outcomes (103 out of 133 publications). The evidence in the existing literature of the share of individual and community outcomes is somewhat contradictory. For instance, a similar review with a final sample of 35 empirical studies, Stepenuck and Green (2015) recorded an almost equal share of individual (25 articles) and community outcomes (24 articles). However, Groulx et al. (2017), in their systematic review of 64 included publications, observed more nature-based CS climate change learning outcomes at individual than community levels. One reason for this could be that individual outcomes are more easily observed than community changes. Over time, more community benefits could become more apparent and the benefits realised; however, there are still only a few reviews on community outcomes to be able to give some more substantial reasoning here. Our data though suggests that in many publications, multiple outcome sub-types (individual and community outcomes) occurred in the same publications, supporting each

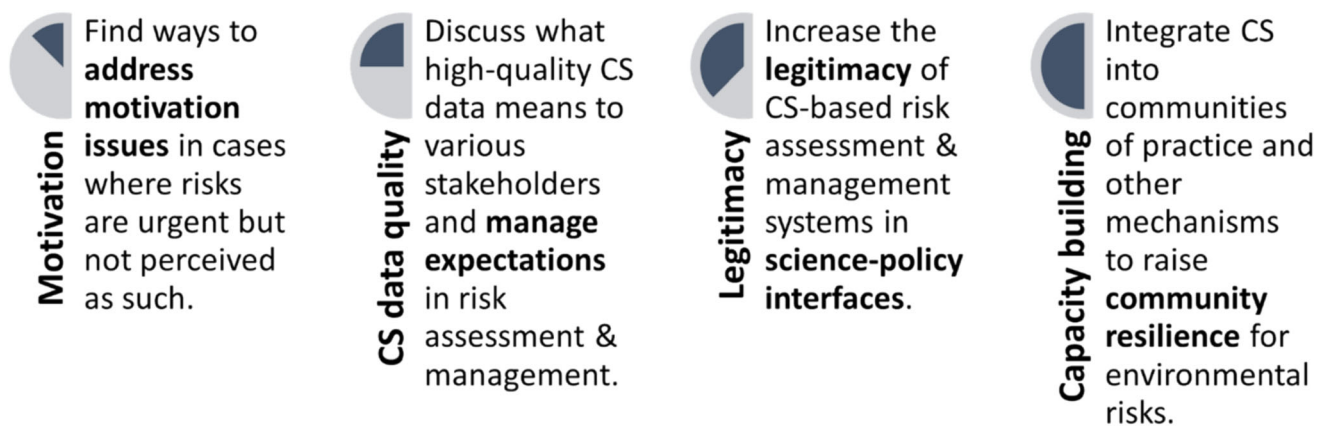


Fig. 8 CS-based environmental risks assessment and management implications (Source: the authors)

other: for instance, awareness or knowledge acquisition was referred to as actionable knowledge, combined with skills and/or community capacity which suggests that knowledge does not remain theoretical but will likely be or has already been implemented.

In our sample, the most recorded individual outcome was increased knowledge, but other individual-attributed outcomes, e.g., interest, motivation, skills, were also frequently represented. This is generally in-line with other reviews (Groulx et al. 2017; Peter et al. 2019). The most recorded community outcome in our sample was community awareness, closely followed by community action. This differs somewhat from previous reviews, e.g., where in addition to community awareness, social capital (Stepenuck and Green 2015), or building new relationships (Groulx et al. 2017) were mostly observed. These differences can be attributed to the domain specificity we reviewed: environmental risks require more immediate and concrete steps to be taken (i.e., action) than the more general environmental monitoring and biodiversity CS projects' contexts. However, a more concrete outcome category comparison is not possible due to differences in the community outcome categories, e.g., attitudes being assessed at community level as well (Stepenuck and Green 2015). Also, articles in our sample reporting on individual outcomes did not necessarily report community outcomes (and vice versa). This was, however, not the case for certain outcome types, e.g., individual knowledge and community awareness or actions which were often mentioned together in the same studies (Supplementary 6). Such uncertainty and unknown linkages could also point to a knowledge gap. For instance, certain individual outcomes, e.g., motivation and interest, are crucial to the viability of CS projects (West and Pateman 2016); thus, it would be important to know, how these outcomes support each other and what is their role in different CS engagement levels.

Walker et al. (2021) reviewed 549 publications in the water management domain, where he noted potential CS benefits are more often recorded than actual benefits and 24% of the publications in their sample did not mention any impacts. In the actual benefits category, they distinguish between inferred (reported but not investigated outcomes, e.g., knowledge gain, scientific literacy) (12%), observed (outcomes observed, e.g., raised awareness, behavioural change) (13%) and investigated (i.e., outcomes studied, with pre- and post-project study design) (16%) benefits (ibid.). Our synthesis, however, did not distinguish between outcome categories based on study designs. As the UN Office for Disaster Risk Management (UNDRR 2017) states, the community's ability to perform risk assessments and manage risk are essential for building resilient communities. It is, therefore, imperative in future reviews that perceived benefits from CS projects are investigated rather than just inferred, to ensure the benefits had accrued to the communities.

CS-related environmental risks assessment and management implications

We identified four CS-focused risk assessment and management implications in the environmental domain (Fig. 8).

First, citizen scientists' **motivation** is central to the success of CS tools, yet it appears to be among the greatest CS projects' challenges (West and Pateman 2016). Environmental risk assessment and management is a specific field here, as citizens often perceive they benefit from such activities. In our sample, we observed where acute risks (e.g., flooding, volcanic threats) or health risks (e.g., air pollution) were likely, the involvement motivation in relevant CS-based monitoring mechanisms was not an issue (e.g., Stone et al. 2014; O'Grady et al. 2019; Durkin et al. 2020; Cornwell et al. 2024). However, in less risk-prone

cases (e.g., monitoring flooding in less susceptible areas) provoking or retaining volunteer motivation was a problem (O’Grady et al. 2019). Similarly, higher overall social capital (e.g., a sense of moral obligation to the community) or other characteristics (e.g., monitoring attracting attention because of safety concerns) appear to be helpful (Stone et al. 2014; O’Grady et al. 2019; Micheli et al. 2024). Drawing on motivation factors in the existing CS literature, suggestions for increasing motivation in the environmental risk domain range from clarifying CS project aims, systematically monitoring and managing citizen scientists’ expectations, to involving citizen scientists beyond the data collection phase (West and Pateman 2016).

Second, the CS-sourced data **reliability and usability** appear a concern, especially where the high input accuracy is needed for environmental risk management (Florin and Bürkler 2018), as CS data are highly susceptible to measurement and geostatistical errors. CS data quality issues (e.g., data accuracy and precision, spatial and temporal biases) and ways to address those (e.g., standardised sampling procedures) are widely discussed in the CS literature (e.g., Balázs et al. 2021), some of which we also observed in our included studies. For instance, as CS data collection relies on citizens’ mobility, but also their interests, an example is air pollution CS initiatives, where monitors tend to pay more attention to polluted spots (Sîrbu et al. 2015). Proposed solutions addressing such issues range from awareness raising of the importance of data quality standards (Balázs et al. 2021), to specific measures, which were also mentioned in our sample, e.g., paying attention to monitor locations and timing in instructions and guidelines (Sîrbu et al. 2015; Froeling et al. 2024). In risk management, where ambiguity and complexity are often high (Renn et al. 2011), it is important to establish procedures for CS projects, which enable open discussions on data quality issue, and to ensure quality control procedures are agreed upon by all project participants and potential data users.

Third, a related issue is **the CS-sourced knowledge relevance and legitimacy** to various stakeholder communities, including policymakers. The challenge of integrating various knowledge types (e.g., technical expert knowledge, experiential local knowledge) is recognised in the risk governance literature (Renn et al. 2011; Webler and Tuler 2021). We detected similar issues in our sample. For example, CS is useful in risk management, especially to “*anticipate and mitigate hazards, and to support better planning*” (Cieslik et al. 2019), but generally it is understood that CS knowledge is “discounted” compared to “official” scientific knowledge (Allen 2018; Ramírez-Andreotta et al. 2023). From a local community standpoint, CS-based data represents a significant opportunity for acquiring information pertinent to community needs in

addressing the community vulnerabilities (Pérez-Arévalo et al. 2024). An example is CS related to environmental pollution, coupled with health issues, where CS has enabled citizens to take proactive measures to protect their health (e.g., Raheja et al. 2022; Jain et al. 2024). However, challenges remain in translating such data into actionable insights at a larger scale for local communities (Pandeya et al. 2020). These challenges can be addressed via improving accountability and addressing trust issues in CS-based warning systems (McCormick 2012; Marchezini et al. 2017), as well as via relevant educational initiatives (Joseph et al. 2019; Ramírez-Andreotta et al. 2023).

Fourth, our synthesis shows **community resilience capacity building** is increasingly documented as a CS project outcome and is as important as the data sourcing. Education for more informed coping mechanisms for risks is an immediate collateral effect of CS programmes. This is achieved through training in monitoring skills and the utilisation of collected data (Stone et al. 2014; Matz et al. 2017; Joseph et al. 2019; O’Grady et al. 2019; Wong et al. 2020), for example, the direct transfer of environmental risk information to local school curricula. CS plays a role in social and human capital development, including nurturing communities of practice (Matz et al. 2017; Hsu et al. 2018; King et al. 2021), engaging volunteers in environmental justice and health concepts (Raheja et al. 2022), and developing capable leadership to promote risk avoidance decisions (Stone et al. 2014). In many publications, power redistribution, equity/justice and individual and community empowerment to advocate for themselves was highlighted. This supports the idea that communities can organise their risk management partly independently from or in closer collaboration with governmental bodies, which in turn allows a more efficient risk response (e.g., faster evacuation, personal/community protective behaviours) (Stone et al. 2014; Jain et al. 2024). This emerging direction also highlights many questions regarding future research in CS for those projects dealing with developing engagement approach mechanisms, both for local communities or for reaching relevant decision-makers or research expertise (Stone et al. 2014; Matz et al. 2017; Joseph et al. 2019; Hahn et al. 2020; King et al. 2021).

Limitations

As mentioned, due to the resource constraints of a small team, searches were limited to two academic search platforms (WoS, Scopus) and the “Citizen Science Theory and Practice” journal; empirical articles; and English publications. This approach could have excluded information available, for example, governmental project evaluations or citizen-based monitoring, which can feature in the grey literature (e.g., McCormick 2012), especially in other

languages. However, although this review only assesses the CS academic literature, it can still be useful to promote dialogue towards increased academic assessment of risk governance in the future.

Our review makes no quality assessment of the science produced by the CS projects. Involving the public in science does present several issues, such as the acceptability of the science quality by officials due to the public's lack of knowledge. However, this has been covered in the CS scientific literature and generally discounted with the appropriate safeguards such as training, education and proper use of equipment (Allen 2018). This perhaps also highlights the issue that it is due to the lack of knowledge amongst officials that highly relevant and timely CS data is available and useful. Community-based monitoring is crucial to increase community resilience in communities at risk from environmental disasters (UNDRR 2017), likewise scientists benefit from having access to increased monitors with an increasing knowledge base as projects progress (Suškevičs et al. 2024). Our focus, therefore, was on how citizens have been incorporated into the projects along with the learning outcomes involved to demonstrate the utility of including CS in risk governance and management.

CONCLUSIONS

This review draws on a systematic evidence synthesis from $n = 133$ publications where citizen science intersects with environmental risk assessment and management. We next briefly revisit our research questions. First, *what are the individual and community outcomes of environmental risk-related CS?* We identified several benefits for individuals and communities dealing with environmental risks, which range from individual knowledge and scientific skills' gains, altered motivation and increased interest towards the study objects or science in general. Many publications indicated community outcomes too, foremost community awareness, community actions and community capacity. Second, *do the outcomes differ when citizens participate via different CS engagement models?* Our analysis suggests that outcomes indeed tend to differ, foremost in terms of contributory CS having a larger proportion of articles mentioning individual outcomes (and no outcomes at all) than collaborative and co-created CS. However, a more specific and quantitative comparison of these three CS models and their outcomes was not feasible due to the small numbers of articles representing each CS engagement level in our current sample. Third, *what are the results implications for the environmental risk assessment and management design?* We draw three main conclusions about the implications. First, this synthesis has shown that

CS has benefits for risk governance at individual and more importantly at community level. Thus, it potentially increases community resilience to face the risks exacerbated by global hazards (e.g., those induced by climate change). Therefore, building knowledge and science literacy through improved science/public interface in a trusting environment has far greater implications for health and wellbeing of local communities. CS projects are important for environmental monitoring, but in the case of risk management, it can mean the difference between life and death, where actionable knowledge that can and will be implemented is crucially needed. In today's rapidly changing climate and land use where environmental disasters can lead to conflicts and conflicts lead to environmental impacts, it is vital scientifically knowledgeable communities can respond to environmental disasters to contribute to long-term stability.

We note that CS is being increasingly acknowledged but has not yet been fully recognised as a beneficial tool in the risk assessment and management domain. The evidence of more collaborative CS models (collaborative, co-created CS projects) appears less widespread in the risk-related CS. Still, if CS aims to achieve outcomes beyond the individual level, our findings indicate that co-created projects are particularly effective in delivering community-level outcomes. Also, CS tends to be used more in the early risk governance phases (e.g., early warning, risk appraisal) and risk management, than in specific phases evaluating risks in detail (e.g., risk characterisation and evaluation). However, the CS process has the potential to increase the monitors on the ground and improve knowledge of community risks, in addition to increasing data acquisition. This strengthens local community knowledge of the risks, enhancing their ability to understand it and take appropriate actions.

We identified key future research directions, which include studying CS' benefits for specific risk governance phases; and community CS outcomes in different geographical regions (e.g., global North/South). To close the gap between practice and acceptance by decision-makers needs evidence to demonstrate CS effectiveness (both in terms of primary research and reviews). Understanding which processes improve the governance and management of environmental risks is imperative to protect the health and wellbeing, even the lives, of vulnerable communities.

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Declarations

Conflict of interest The authors declare no conflict of interest related to this research.

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