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The contributions of Indigenous People's earth observations to water quality monitoring

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Indigenous Knowledge, observations and understandings of Earth processes are not sufficiently included in global Earth Observations. Drawing on the results obtained during a 3-day hackathon event, we present evidence, best practices and recommendations to water quality organizations seeking to engage and share information with Indigenous communities. The hackathon event revealed three key findings: First, Indigenous Peoples report precise and accurate observations of changes in various Earth systems, particularly the hydrological cycle. Second, this information can significantly enhance global Outreach and Engagement efforts, aiding in the understanding of hydrological cycle components, water quality, mapping water courses, and monitoring and mitigating the effects of climate change (i.e., floods, droughts, etc.). Third, enabling Indigenous Peoples to contribute their scientific knowledge and utilize Earth Observations is crucial for the protection of other vital components of the water cycle. We addressed two crucial questions: What opportunities exist to include Indigenous Knowledge into Earth Observations, and what are the main challenges in doing so?

KEYWORDS
Indigenous science, water quality, Earth Observations, water monitoring, data sovereignty, GEO Indigenous Alliance, Indigenous Knowledge

1 Introduction

Indigenous Knowledge (IK) includes skills, practices and custodial responsibilities that are sustained and passed down through generations, which often forms part of their spiritual identity and contributes to conservation (e.g., assessing forest, water resources, fisheries, wildlife, etc.) (Berkes, 2012; Garnett et al., 2018; López-Maldonado, 2021). Through intergenerational experience and precise observations, Indigenous Peoples (IP) were among the first to observe and understand complex processes on Earth, notice changes in natural phenomena, and gain critical knowledge to adapt to environmental and climate changes (McElwee et al., 2020; Jessen et al., 2022; Turner et al., 2022; Reyes-García, 2023).

In scholarly and policy circles, there is a growing recognition that IP possess unique knowledge and understandings of the natural world (López-Maldonado, 2021; Reyes-García et al., 2024a,b) and that they can provide valuable information to address current environmental challenges to reach global goals. IK and IP can provide detailed information on local-scale Earth features. For example, they can detect how climate variability and Earth system changes affect their livelihoods. This might support new global technologies for monitoring Earth processes and enhance transformations toward sustainability. Australia, for example, produces a national State of the Environment report every 5 years, and in 2021 it combined scientific, traditional and local knowledge. Indigenous and non-Indigenous people have worked together to create this first holistic assessment of the state of Australia's environment. The report aims to help shape policy and action, influence behaviors, and assess the effectiveness of interventions to improve Australia's environment (Cresswell et al., 2021).

Recently, valuable information has been gained through the utilization of Earth observations (EO), a term commonly defined as the acquisition of data from the Earth's surface and atmosphere through remote sensing instruments. EO-based water quality information combines satellite data, unmanned aerial vehicle (UAV) and *in situ* water sampling of optical properties and water quality parameters. The combination of modern space and *in situ* technology plays a key role in understanding water quality, global water cycles, mapping water courses, and monitoring and mitigating the effects of stressors such as floods and droughts. However, current EO data/products for water quality do not connect knowledge and scales easily (CEOS, 2018), and IK and local observations are often overlooked (Rattling Leaf Sr, 2023). Incorporating IK and observations into the development of EO applications can help us better understand dynamic Earth conditions and the implications of long-term changes (GEO Indigenous Alliance, 2021; Hauser et al., 2023; Letaapo, 2023; Rattling Leaf Sr, 2023).

The complexity of IK, however, is not only observed in EO applications but it also extends to several interrelated levels of analysis ranging from the local level (e.g., precise knowledge of species), to the understanding of complex ecological and processes on a global scale (e.g., accurate knowledge of the hydrological cycle) (López-Maldonado, 2021). The growing recognition of the importance and value of IK is also the result of its local representation which is a valuable resource to validate large scale observations and modeling tools that support scientific research (Angarova et al., 2022). For example, because the Earth's dynamics are connected to broader environmental and biological processes, IK and local observations may include one or more important connections and evidence of other processes and changes that might go unnoticed on a global scale (Deemer et al., 2018).

Indigenous communities not only possess a deep understanding and monitoring of water and atmospheric processes, such as changes in climate and water quality and their relationships with other components of the hydrological cycle, but also offer precise and accurate knowledge of other complex Earth processes (see Table 1). However, IK remains an unexplored source of data with untapped potential to contribute to our understanding of water systems. It is thus both ethical and politically correct to incorporate IK into data and tools, including EO. Crucially, this process should be initiated by IP (Rattling Leaf Sr, 2023). Aquatic science must include IK and understandings of the environment into the measuring and monitoring processes. Including IK with other knowledge systems to understand complex processes on the components of the hydrological cycle will significantly improve the representation and inclusion of locally-based water processes into global models, allowing for better decisions to be made at local to global scales.

In this perspective we report on the results obtained during a three-day hackathon event where a group of water quality experts and indigenous scholars discussed the engagement of IP and IK into water quality monitoring using EO technology. We present evidence of how IP report numerous changes in the hydrological cycle at the local scale, including precise and accurate observations of such changes, and on how this information can inform global outreach and engagement. We also provide best practices and recommendations for water quality organizations seeking indigenous engagement and information sharing, and highlight the importance of building trust and respect with IP.

We aim to foster discussions within the EO community to actively address the underrepresentation of indigenous voices in the cultural integration of water quality management. Additionally, we seek to enhance the capacity of indigenous communities to participate in water-related research, planning, and management, as outlined by Berry et al. (2018). This paper has been led by an indigenous author (YLM) to specifically ensure that this document reflects and maintains indigenous epistemological and methodological approaches to scientific research, while research that incorporates IK is carefully designed to be sensitively conducted, addressing the ethical, fair and equitable treatment of IK.

2 Methodology

The collaborative hackathon event "Innovation Workshop on Water Quality Monitoring & Assessment" (Chernov et al., 2024[1]; submitted to the same collection), held in Petten, the Netherlands, from 27 to 29 September 2023, was attended by 58 experts, 14 of whom focused on contributing to the Indigenous engagement concept development. Among invited participants, more than 25 participants were fully or partially funded to attend the workshop, with priority given to participants from developing countries, indigenous peoples, and underrepresented communities. Participants were assigned to four different challenges based on their expertise. The challenges were selected by the organizers following a call for proposals that generated over 60+ challenge proposals. This perspective paper stems from the challenge proposed by the collaboration among the AquaWatch Australia, the Group on Earth Observations (GEO) AquaWatch Initiative and the GEO Indigenous Alliance who proposed a challenge theme on Indigenous water quality issues entitled Melding AquaWatch

1 Chernov, I., et al. (2024). Innovative solutions for global water quality challenges: insights from a collaborative hackathon event. Submitted for this same collection.

TABLE 1 Examples of Indigenous People's EO of changes in the water cycle reported on the scientific literature*.

Example	Description	References
Groundwater	The Mayas of Yucatan have a particular worldview and knowledge related to the use of underground water caves (locally called cenotes). Cenotes are formed because much of the water that falls as rain infiltrates into the ground creating a stream that disappears underground in a cenote, recharging the aquifer. To survive in a region with no surface waters, the ancient Maya had to engage in collective groundwater management. The hydraulic system engineered by the Maya was able to adapt to the evolving needs of a growing population (3 million to 13 million over several hundred years). To deal with seasonal variations in rainfall, the Maya developed strategies for storing and managing water. They learned how to build reservoirs to capture rainfall. They constructed dams on the top of hills, so as to use the slopes to distribute water through canals in a complex irrigation system.	López-Maldonado, 2014, 2021; López-Maldonado and Berkes, 2017; López-Maldonado et al., 2017
Cryosphere	Indigenous groups across diverse regions of the world have adapted to regions where water can be found in a solid frozen state such as ice caps, glaciers, snow and permafrost, which occur in polar areas. Indigenous groups in the Arctic, for example, have adapted to this environment since time immemorial and they have been reporting numerous observations and place-based indicators of change. For example, Inuit communities of Alaska have been working with a network of *Iñupiaq* observers from northern coastal communities on local-scale environmental observations including sea ice growth, dynamics, and decay; shore-based and drift ice measurements of ice motion, key mass balance variables, and ice properties among many others. Reports of changes, and joint ice-mapping activities, etc. have provided a link between geophysics and indigenous sea ice experts.	Krupnik and Jolly, 2002; Laidler et al., 2011; Druckenmiller et al., 2013; Deemer et al., 2018; Hauser et al., 2023

*All indigenous authors in the publications listed were fully acknowledged.

& Global Indigenous Knowledge (MAGIK): "*Finding value in data sharing: ensuring trust and relationship building.*" This collaboration is based on AquaWatch Australia's implementation of integrated ground and space technologies to monitor water quality around the world and provide the monitoring and forecasting of water quality data like a weather service. The use of such technology coupled to a global EO water quality community of practice (GEO AquaWatch) and an Indigenous-led conduit for indigenous engagement within GEO (GEO Indigenous Alliance) can lead to innovative solutions to improve the representation and inclusion of IK into global water quality data generation (Figure 1).

The event format was a hackathon where within each challenge, participants contributed to formulating sub-challenges and selected their focus area from two sub-groups: The Jennings et al. (2023) and UNESCO (2023) papers were recommended advance readings. Within the MAGIK challenge, one subgroup was dedicated to discussion of trust-building and capacity development best practices for successful engagement in knowledge-sharing with indigenous communities, and the other subgroup addressed technical aspects of data sovereignty, security and storage capacity, and workflow processing in the EO water quality realm. A central theme in both subgroups was to identify the main challenges and opportunities to including IK into EO for water quality studies. Subgroups also collaborated in plenary sessions, addressing conference-wide goals and activities, culminating in live pitches by each subgroup to convey key messages.

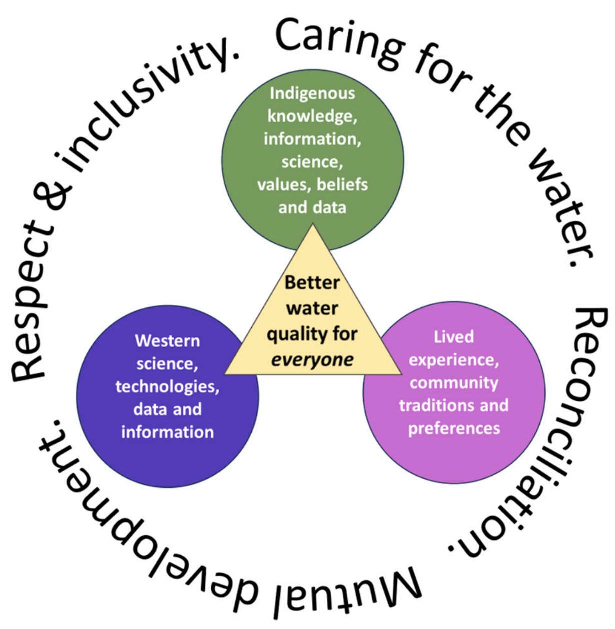

FIGURE 1
Diagram of EO-IK relationships and foundational principles of the MAGIK alliance.

3 Results

The outcomes of our discussion are presented in three themes related to the sub-challenges: (1) Review of concrete case studies illustrating how IP effectively utilizes EO data and their IK to substantiate compelling evidence of multiple environmental changes. (2) Identification of the main challenges inherent in the integration of EO and IK systems, and (3) A set of policy-science recommendations that have emerged from these discussions and highlight a pathway to advance the inclusion of EO and IK in the field of water quality monitoring and assessment.

3.1 Indigenous peoples report detailed evidence of changes in water systems

Water is considered a center of people's lives in indigenous communities as they believe it is connected to their ancestors; it is their traditional belief, therefore it is part of their communities' identity (Nguyen and Ross, 2017). As such, indigenous communities are following changes in weather that have direct and indirect effects on the water systems through IK so that they can adapt to ongoing changes (Reyes-García et al., 2024a). Similarly, communities are effective at implementing conservation measures because they are part of nature and depend on ecosystem services to complete the natural system (Inaotombi and Mahanta, 2019; Letaapo, 2023; Vargas Shakaim, 2023). Changes in important components of the hydrological cycle particularly on freshwater have been also reported by diverse indigenous groups through their observations (Prober et al., 2011; Somerville, 2014; López-Maldonado, 2021) (Table 1). For example, specific observations on sea ice thickness, snow cover and ocean conditions are compiled regularly by IP in the Arctic (ICC-Alaska, 2016). Similarly, the gathering of the clouds and the sounds of birds and insects are used in the determination of the weather by IP in forest environments (Tume et al., 2019). Likewise, loss of some of the indicators traditionally used in the past calls for new tools and approaches to support communities in making informed decisions (Gratani et al., 2016; Letaapo, 2023).

3.2 Challenges to include Indigenous Knowledge into EO

In this section two types of challenges are presented, including those encountered by participants during the hackathon event in trying to reach agreements, and those associated with the inclusion of IK into EO more generally. Early discussions focused on the acronym "MAGIK," with concerns raised about potential negative connotations, such as associations with the supernatural or stereotypical views of IP. The term "melding" was also scrutinized due to its implication of assimilation into Western science, raising concerns about integrity loss and ties to scientific colonialism. In bridging Indigenous and Western science, indigenous communities may not always understand the language of water management and Western science. On the contrary, water management authorities often lack a clear understanding and appreciation for Indigenous cultural values and scientific thought (Moggridge and Thompson, 2021). Concerns about the explicit association with the AquaWatch Australia and GEO AquaWatch were also mentioned since they may constrain the apparent relevance of the main theme to a wider global audience. Manipulating indigenous communities and their knowledge to achieve outreach metrics was also a topic of discussion. For example, AquaWatch Australia aims to provide "superior" modern technologies, but this could be interpreted as harming or eroding Indigenous leadership.

During the hackathon discussions were extended to the challenges associated with the inclusion of IK with EO. Figure 2 presents a word cloud with the main topics arising from those discussions. Key considerations included the need to co-construct mechanisms for data sharing with Indigenous communities. This approach, participants argued, was essential to promote the co-development of new knowledge and prevent the appropriation or misuse of IK for the benefit of non-Indigenous organizations. For example, IK is often an after-thought, rather than an inherent component of research plans. Similarly, sustainable project funding, and building lasting relationships between indigenous communities and researchers, has proved crucial to avoiding the pitfalls of "helicopter-style" projects that could undermine trust. Despite the expressed interest, the inclusion of IK into research programmes is still often neglected during implementation.

These nuanced deliberations resulted in recommendations for policymakers and academics. Non-indigenous participants were in favor of actively engaging with indigenous communities to contribute to the Sustainable Development Goals (SDGs) for water quality and to be guided by the principles of the United Nations Declaration on the Rights of Indigenous Peoples (UNDRIP). They emphasized the importance of maintaining momentum within the MAGIK community, and supported the growth of the MAGIK community from within the GEO Indigenous Alliance, World Water Quality Alliance, AquaWatch Australia and GEO AquaWatch, focusing on sustainability, and calling on the GEO Secretariat to officially support and recognize the GEO Indigenous Alliance. Identifying or developing funding opportunities to build capacity within indigenous communities to enable joint initiatives between the GEO Indigenous Alliance, GEO AquaWatch and AquaWatch Australia was a key recommendation. Building stronger links with organizations such as the Global Indigenous Data Alliance (GIDA) was also highlighted. The call for a collective revision of the MAGIK name and the invitation by the GEO Indigenous Alliance to MAGIK participants in various international high-level events, emphasized the commitment to the inclusion of indigenous perspectives in global water quality initiatives. Disconnection of indigenous needs and priorities with research was also raised including the lack of support of indigenous scholars.

3.3 Key recommendations

During the course of the challenge discussion, a number of policy-oriented recommendations emerged, providing paths on how to engage with IP, their knowledge and scientific though in the context of water quality research and monitoring.

3.3.1 Overall policy recommendations

- Respect IK as part of a knowledge system: this includes recognizing that this knowledge may not be available to other knowledge systems, and may or may not be bridged. This includes respecting indigenous protocols when working with IK-holders as well as when accessing and using shared knowledge.
- Support IP in maintaining and increasing their knowledge by providing capacity within communities and include communities in the definition of research questions, data collection and interpretation of results.
- Engage with indigenous communities, with free, informed and prior consent, to meet water quality SDGs goals and further contribute to the UNDRIP principles globally.

FIGURE 2
Word cloud of main topics discussed during the event.

- Work in partnership with communities and allow them to be local observers that have their own methodologies for research inquiry.
- Support community-based long-term and local scale environmental observing and monitoring.
- Recognize past and current role of institutions: non-indigenous scientists and policy makers are to be aware of past and ongoing impacts of colonial ways of doing when working with indigenous communities. Meaningful support is required to enable IK to be maintained and increased. According to McGregor et al. (2023), “institutions need to do work to build respectful, reciprocal relationships for possible cooperation or partnerships to take place.”

3.3.2 EO/IK specific recommendations in the context of the MAGIK challenge

- Maintain the momentum and support the growth of the MAGIK community from within the GEO Indigenous Alliance, World Water Quality Alliance, AquaWatch Australia and GEO AquaWatch.
- Focus on project sustainability by generating tangible outcomes that can be directly translated into actionable steps.
- Advocate for increased efforts by the GEO Secretariat to formally increase their efforts to support indigenous engagement on water quality, through support of the GEO Indigenous Alliance.
- Support and invite indigenous scholars to develop research based on their own indigenous frameworks, methods, tools, and approaches.
- Communicate IP observations of the environment ensuring, to the extent possible, their worldviews are represented.
- Seek funding to complete a project to prioritize indigenous engagement on water quality monitoring globally. Propose a joint initiative involving GEO AquaWatch, AquaWatch Australia, and the GEO Indigenous Alliance.
- Establish stronger connections to the Global Indigenous Data Alliance (https://www.gida-global.org/), who are an international network promoting indigenous control of indigenous data and information.
- Collectively review whether the name MAGIK should be changed.
- Invite GEO Indigenous Alliance Members interested in water quality into the MAGIK network.

Several of the above recommendations can be addressed by supporting IP in developing data governance frameworks to support Indigenous data sovereignty, as underpinned in Article 31(1) of UNDRIP. Data sovereignty can be defined as “the right to maintain, control, protect and develop cultural heritage, traditional knowledge and traditional cultural expressions, as well as the right to maintain, control, protect, and develop intellectual property over these” (Kukutai and Taylor, 2016).

4 Discussion

4.1 Capacity building and indigenous-led participatory research

The recommendations stemming from the hackathon offer practical measures to enhance opportunities for water quality capacity building prospects within Indigenous communities. Fostering improved water quality outcomes co-constructed with

IP can yield to decisions that better reflect community needs and that are meaningful, supported, and lasting. Participatory Indigenous-led research has often been proposed as a preferred model because it engages IP in the research process which builds awareness of the great value and benefit that IK can bring to all aspects of the research design and implementation process (ICC-Alaska, 2016).

Emphasizing the need to instill respect for Indigenous science, knowledge, and communities at the global level, these recommendations lay the foundation for a more inclusive and equitable collaboration. Moreover, the call to co-construct new Indigenous-led tools and approaches, aligning with Indigenous perspectives on addressing the impacts of climate change on Indigenous communities, demonstrates a commitment to diversifying perspectives in EO practices (Rattling Leaf Sr, 2023). Furthermore, acknowledging Indigenous-led initiatives, such as the GEO Indigenous Alliance, as the conduit for facilitating indigenous engagement within the scientific community underscores the significance of authentic representation and amplification of IP voices in global initiatives.

4.2 The imperative to include IK into EO

Observations made by IP provide an independent and rich dataset and documentation, with a high level of detail that is usually not included in global EO. These data can be correlated to historical measurements captured through global EO instruments, and can also better inform efforts to adapt and improve the resilience of water ecosystems in future. The opportunities identified in this paper to incorporate IK and observations into global EO practices and policies serve as a strategic roadmap for maximizing impact from our findings. These recommendations range from expanding participation in global initiatives (e.g., GEO AquaWatch, GEO Indigenous Alliance, AquaWatch Australia), to recognizing the rights of IP in co-designing EO products, and fostering a comprehensive and respectful integration of IK and western science. The call for the development of best practice approaches (two-way science), including Free and Prior Informed Consent (FPIC) and Indigenous Cultural and Intellectual Property (ICIP), underscores the ethical imperative when undertaking community projects. Implementing these recommendations represents not only a practical next step, but also a commitment to the principled co-construction of knowledge that underpins a sustainable and harmonious future (Bardwell and Woller-Skar, 2023).

A range of opportunities to continue building momentum within the MAGIK community were identified at the hackathon. The GEO Indigenous Alliance extended invitations for selected MAGIK participants to showcase their work at events like the GEO Dialogue Series, the GEO Indigenous Water Summit, the UN Climate Change Conference (UNFCCC COP 28) and to act as mentors at the GAIA4All Indigenous Hackathon for Early Warning Systems. Presentation of the MAGIK challenge showcased at GEO Week 2023, and the insights shared at the GEO Indigenous Water Summit, highlights the impact of the workshop and emphasizes the broader recognition and integration of Indigenous perspectives in global dialogues and initiatives.

5 Conclusion

We anticipate that this perspective paper will contribute to fostering a wider understanding, acceptance, and support of IK by non-Indigenous researchers. One key challenge for researchers lies in identifying research methods that genuinely incorporate IK, to improve western science, as distinct from merely acknowledging Indigenous or cultural knowledge. The recommended model is for Indigenous-led participatory research, based on Indigenous understandings, frameworks and conceptions. These projects should be action oriented, focused on respect, reciprocity, and mutual responsibility. This is an increasingly common model in countries such as Canada, Australia, and New Zealand which have been actively addressing culturally appropriate research design with Indigenous communities over the last few decades.

In terms of water quality, there is a pressing need for ongoing forums that provide a platform for researchers addressing water issues worldwide. Establishing connections between researchers, water experts, practitioners, IP and indigenous scholars can offer new perspectives on global water resource challenges. However, the establishment of these connections should be based on the development and maintenance of trust to advance participatory research. Within GEO, for instance, we call on the GEO community to acknowledge and support the pivotal role of the GEO Indigenous Alliance as one valuable conduit between IP and the broader EO community, using "True Tracks" principles (Janke, 2019) to protect Indigenous IP and self-determination.

Integrating Indigenous-led EO tools is a vital key to finding solutions to water challenges. IK and local observations are a valuable resource with proven reliability, benefiting not only IP but also informing national and international water governance and policy-making. There must be deliberate efforts to include Indigenous researchers in the co-development of research programs focusing on water quality. Indigenous representation is often lacking in the early stages of project planning, which dismisses IP's right to have a say in activities and outcomes on their lands and waters, and significantly underestimates the benefit that IK can bring to improving western science. Only through a genuine commitment to deep collaboration between western science and IK can we achieve better water quality for everyone.

This is the MAGIK challenge, a challenge we enthusiastically embrace, and we encourage others with interest in water quality, IK and IP to embrace it too. Connecting scales and including diverse knowledge systems is essential in developing integrated monitoring systems and can provide more robust information to help us to adapt and to be resilient in the face of climate change.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent for participation was not required from the participants or the participants' legal guardians/next of kin in accordance with the national legislation and institutional requirements because written informed consent from the participants was not required to participate in this study in accordance with the national legislation and the institutional requirements.

Author contributions

YL-M: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing—original draft, Writing—review & editing. JA: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing—original draft, Writing—review & editing. MN: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing—original draft, Writing—review & editing. JM: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing—original draft, Writing—review & editing. DM: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing—original draft, Writing—review & editing. HN: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing—original draft, Writing—review & editing. IO: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing—original draft, Writing—review & editing. AS: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing—original draft, Writing—review & editing. KS: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing—original draft, Writing—review & editing. NS: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing—original draft, Writing—review & editing.

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Conflict of interest

JA and NS were employed by AquaWatch Australia, CSIRO. MN is employed by Global Science & Technology. DM was employed by GEO Indigenous Alliance & Space4Innovation.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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