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Dialogic data innovations for sustainability transformations and flood resilience: The case for waterproofing data

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ABSTRACT

Extreme weather events are becoming more frequent and have increasing impacts, which disproportionately affect marginalised and impoverished communities. This article proposes and assesses a new methodological approach for developing innovative solutions based on urban data analytics to address sustainability challenges in light of changing climate conditions. The approach draws inspiration from Paulo Freire's dialogic pedagogy and has been implemented in the international transdisciplinary project "Waterproofing Data", with multiple study sites in Brazil. The project has introduced three methodological interventions: making data practices visible, engaging citizens and communities with data, and sharing data stories. Our study demonstrates that these methods have expanded the types of data used in flood risk management and have engaged a wider range of social groups in the generation, circulation, and utilization of data. We present a framework that provides guidance about the ways in which data innovations can contribute to transformative change, aiming to ensure that future development trajectories are just, inclusive, and equitable. The findings provide evidence that our approach not only helps fill existing data gaps and promote more equitable flood risk governance but also democratises decision-making in climate adaptation. Citizens were empowered to take proactive measures to improve resilience to disaster risks, thereby saving lives and safeguarding livelihoods.

1. Introduction

Climate change and the growth of vulnerable populations worldwide have increased disaster-related socioeconomic and environmental impacts. As many as 1.81 billion people are estimated to be directly exposed to significant flood risks (i.e., 1-in-100-year floods), but these risks do not fall equally across the world: 1.61 billion (89%) of the world's flood-exposed people live in low- and middle-income countries (Rentschler et al., 2022). Even in high-income countries such as the United States of America, lower-income populations are more impacted by floods, with black and minority ethnic people expected to be disproportionally affected by risk increases in the coming years (Wing et al., 2022). Social research has been arguing for a few decades that there is nothing "natural" about disasters (O'Keefe et al., 1976): disasters only happen when hazards meet conditions of vulnerability (Adger, 2006). Even if climate change is expected to make extreme weather events more frequent and more severe, the climate alone is not to blame for current and potential future disasters (Raju et al., 2022). Not only the intensity and recurrence of these events can be attributed to anthropogenic climate change (Dalagnol et al., 2022), unequal patterns

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of socioeconomic development and urban growth are important underlying root causes of the inequitable risk patterns observed and projected. Climate adaptation action and research must strive for future development trajectories that are not only ecologically safe within planetary boundaries (Steffen et al., 2015) but also include an explicit, transformative focus on justice (Pelling, 2010) and equity (Leach et al., 2018). Otherwise, they can lead to techno-managerial interventions that result in "maladaptation" (Eriksen et al., 2021; IPCC, 2022) that ultimately perpetuates, or even exacerbates existing inequalities and injustices.

Data innovations have been suggested as promising tools to support sustainability transformations (Sachs et al., 2019; UN, 2014). They are usually defined as "the innovative use of data to create social and economic benefits" (Wallace and Castro, 2017) and are frequently associated with the concepts of urban analytics, big data and smart cities (Creutzig et al., 2019; Kandt and Batty, 2021); citizen science, citizen-generated data and crowdsourcing (de Sherbinin et al., 2021; Fraisl et al., 2020; Läummerhirt et al., 2018; Wolff, 2021); and more recently, Artificial Intelligence (Nost and Colven, 2022; Reichstein et al., 2021). A recent review of the literature on data innovations for transformations to sustainability has shown that most studies in this field take for granted the positive outcomes of data innovations for social transformation, whilst the specific transformative pathways through which data can enable change (and for whom) are not concretely discussed or evidenced (Porto de Albuquerque et al., 2021). This is particularly problematic given that the scholarship in critical data studies has eloquently argued for the importance of considering that data – i.e., binary encodings which are stored and processed by digital technological artefacts – are always embedded in the materiality of "data practices" (Bates et al., 2016; Dalton and Thatcher, 2014; Loukissas, 2017). An appropriate understanding of the role of data in sustainability transformations requires close attention to the socio-material practices in which specific digital technologies and datasets are generated, processed, circulated, and used – alongside their governance and emerging power relations.

This broader perspective on data shows that social inequality is frequently associated with data inequality (Cinnamon, 2020; A. Fisher and Streinz, 2021). This is not only due to the profound structural inequalities as to who is profiting from the current data ecosystems (Couldry and Mejias, 2019; Zuboff, 2015). The existing data are also ridden with assumptions and biases that arise from an unequal level of access to digital technology for various social groups (Boyd and Crawford, 2012; Mah, 2017). Data that serve hegemonic and high-income groups are often more detailed in comparison to data for marginalised groups (D'Ignazio, 2017; D'Ignazio and Klein, 2020); data relating to wealthy urban neighbourhoods are much more abundant than data that reflect the needs and worldviews of residents of deprived urban areas (de Andrade et al., 2022; Herfort et al., 2021; Robinson and Franklin, 2020; Thomson et al., 2020). Despite their enormous potential for climate adaptation, innovations that build upon biased data can "automate inequality" (Banks, 2019) by systematically misrepresenting the realities of the most vulnerable. Consequently, data innovations which do not embed a normative concern for data justice (Hoefsloot et al., 2022; Milan and Treré, 2019; Taylor, 2017) will result in maladaptation and exacerbate current inequities. Challenges remain in how to address data biases and meaningfully engage citizens and communities not only for instrumentally "sensing" data that others will make sense of (Porto de Albuquerque and Albino de Almeida, 2020), but for shaping data governance as an opportunity for transformative social innovation and social learning (Leach et al., 2012; Sharp et al., 2022; Trajber et al., 2019) in ways that will promote diversity, safeguard citizens' privacy (Evans et al., 2019), and accelerate sustainability transformations (E. Fisher et al., 2022; Scoones et al., 2020).

Approaches to citizen science (de Sherbinin et al., 2021; Fraisl et al., 2020; Läummerhirt et al., 2018; Wolff, 2021) and transdisciplinary co-production (Caniglia et al., 2021; E. Fisher et al., 2022; Juarez-Bourke and Vilsmaier, 2020; Norström et al., 2020) could significantly contribute to addressing these open challenges related to data innovations since they can be used to mobilise collaborative and inclusive knowledge practices and ways of knowing that may bring about transformative change. Yet, existing research on citizen science is predominantly concentrated in the global North, whilst suitable methods to co-produce data with communities in the global South are still incipient (Wolff, 2021). Several transdisciplinary approaches to socio-ecological systems adopt a narrow definition of data that favours quantitative over qualitative evidence and under-represent social issues (Chmutina et al., 2021; Steger et al., 2021). There still is limited understanding and guidance available for the *processes* of co-producing research for sustainability transformations (J. M. Chambers et al., 2022), and this applies particularly to transformative technological and social innovation (Jimenez et al., 2022; Olsson et al., 2014). There is also a need for stronger evidence of which climate-resilient, transformation *pathways* (Bastiaensen et al., 2021; Bilsky et al., 2022; Denton et al., 2014; Gibson et al., 2016; Henrique and Tschakert, 2021; Leach et al., 2018; Scoones et al., 2020) can be opened by engaging diverse societal stakeholders for co-producing data innovations.

To fill these knowledge gaps, this article presents a case study of a transdisciplinary approach for co-producing urban data innovations for transformations to sustainability based on the dialogic pedagogy of Paulo Freire (Freire, 1996, 2005; Freire and Faundez, 1989) with an explicit concern for climate and data justice. This approach has been developed and evaluated by the transdisciplinary project *'Waterproofing Data: Engaging Stakeholders in Sustainable Flood Risk Management for Urban Resilience'*. An international and multidisciplinary research team from three countries (Brazil, Germany, UK) have co-created and co-evaluated this approach with flood risk management professionals, local government officials, local researchers, university students, as well as community members and school students living in underserved, flood-prone neighbourhoods in Brazil (see Supplementary Material for details). Whilst previous publications of our team have presented results of specific components of this project (Calvillo et al., 2022; Coaffee et al., 2021; Klonner et al., 2021; Marchezini et al., 2022; Pajarito-Grajales et al., 2022; Tkacz et al., 2021), this article introduces an integrative perspective of our methodological approach, as well as an empirical evaluation of the project as a sustainability transformation experiment (Weiland et al., 2017), seeking to answer two research questions:

R1. Which methodological processes can enable the co-production of transformative urban data innovations?

R2. Which transformation pathways can emerge from the co-production of urban data innovations?

By answering these questions, this article makes two main contributions to research, policy and practice:

- **A dialogic process for co-producing data innovations**: We present and evaluate a methodological approach for transdisciplinary co-production of data innovations which draws on the dialogic pedagogy of Paulo Freire guided by principles of climate and data justice towards ensuring more just, equitable and ecologically safe futures.
- **A framework for data-enabled sustainability transformation pathways**: We present an emerging framework with six co-produced transformation pathways and show evidence of how they have been unveiled by the outcomes of our project.

The remaining sections of the paper are structured as follows. Section 2 presents an overview of our methodological approach. Section 3 presents the main methodological interventions of the project. In Section 4, we present evidence of outcomes achieved in our project which led to our framework of data-enabled transformative pathways. Section 5 presents a discussion of the main contributions of this study, followed by a conclusion (Section 6).

2. Conceptual framework: A dialogic approach to co-producing data innovations for transformations to sustainability

Our methodological approach is inspired by the concepts of "compositional methodologies" and "problem spaces", as developed by Celia Lury (Lury, 2021; Lury and Wakeford, 2012). Instead of regarding problem spaces as static containers for problems, Lury proposes that compositional methodologies require shifts in both problems and problem spaces. In our context, we are interested in a methodology that can not only deepen the understanding of socio-ecological relationships through data (i.e., address the "problem") but also shift their problem spaces to open up just, equitable transformation pathways to climate resilience and sustainability. This requires *methodological interventions* that shift the problems and problem spaces of research on data innovations towards participatory approaches that seek to co-produce transformation pathways with a normative orientation towards climate justice and data justice.

To perform these methodological interventions, we draw on the dialogic pedagogy of the Brazilian philosopher and educator Paulo Freire (Freire, 1996, 2005; Freire and Faundez, 1989). Since Freire's pedagogical approach has been first proposed in the 1970s based on experiences of literacy programmes in Brazil and Latin America, it has been widely influential in the fields of critical pedagogy and development studies (R. Chambers, 1997), and his ideas have also inspired research on climate adaptation, public participation, and transformations to sustainability (Carvalho and Nunes, 2013; Mehta et al., 2021; Pelling, 2010; Souza et al., 2019; Vilsmaier et al., 2020; Vogel and O'Brien, 2022). Despite this wide acknowledgement of Freire's works, we concur with (Juarez-Bourke and Vilsmaier, 2020) that Freirean principles are yet to be systematically incorporated into collaborative research practices. We argue that Freire's methodological approach is a powerful and as-yet underexplored resource to resituate the problem spaces of transdisciplinary research on data innovation to support social change towards sustainability transformations.

As first proposed by Porto de Albuquerque and Albino de Almeida (2020), we use Freire's dialogic pedagogy to go beyond perspectives solely focused on data's epistemological value, broadening the focus of research on citizen engagement with data to include a "pedagogical lens", i.e., a careful concern with the modes of engagement with which citizens interact with data. This is in line with a nascent stream of studies proposing the concept of critical data literacy (D'Ignazio and Bhargava, 2015; Fotopoulou, 2021; Gray et al., 2018; Sander, 2020; Tygel and Kirsch, 2016). In Freire's liberation pedagogy for "popular education" (Freire, 1987), the educational process is indissociably associated with the development of *critical consciousness* ("conscientização") about the situations in which educators and learners are immersed. Analogously, we consider the research on 'reading and writing data' as an opportunity to develop critical consciousness that can empower us to "read and write the world" (Freire, 1989, 2000).

Freire proposed that this enlarged scope for literacy must be achieved by moving away from an education system focused on training learners to recite the "right" answers pre-defined by the teachers; a procedure which he compared to a "banking system" seeking to make "deposits" in the learners' minds. Instead, we should strive for a "pedagogy of questions", i.e., a "problem-posing" practice ("problematisation") which can only be achieved through the core instrument of the *dialogue*. Importantly, dialogue for Freire does not equate to colloquial meanings which include any type of chat or conversation, but he uses "*dialogics*" (which could also be translated as "dialogicity") in a more specific sense, as a core principle of his method. Dialogue in Freire's work acquires the status of a methodological approach for learning and knowing, i.e., a mode of engaging with other human beings and their situations that is "indispensable to the act of cognition which unveils reality" (Freire, 2000, p. 83).

Central to Freire's dialogic approach is attention to *situationality*: the dialogue must "pose the existential, concrete, present situation to the people as a problem which challenges them and requires a response—not just at the intellectual level, but at the level of action" (Freire, 2000, pp.95–96). For doing this, his literacy programmes started by looking for the "generative words" (later expanded to "generative themes"), i.e., words that are part of the vocabulary universe embedded in the concrete, existential situations of people. Similarly, we propose that a dialogic approach to data innovations for sustainability transformations should adopt the principle of situationality to look for the "*generative data*": i.e., the starting point for the research should be in the concrete *situations* and lived experiences of different people, which include not only their actions, views, and concrete experiences of socio-ecological relationships, but also the data they currently generate, circulate, and utilise concerning socio-ecological phenomena.

Freire's dialogic approach to knowledge and learning entails the development of a new critical consciousness as an instrument for transforming their oppressive realities. Freire's methodological approach to transformation and social change builds upon the *situational analysis* of concrete circumstances and practices to identify "*limit-situations*", i.e., obstacles to liberation that "stand out in relief from the background, revealing their true nature as concrete historical dimensions of a given reality" (p. 99). For Freire, the full understanding of a limit-situation entails the revelation of the potential avenue to overcome it, which he calls a "*feasible unseen*" ("inédito viável"),[1] i.e., a new pathway forward to transcend the limit-situation which had not been visible so far.

Bringing Freire's insights to the context of sustainability transformations, our approach to dialogic data innovations (depicted in Fig. 1) starts with grounded understandings of current situations (*situational analysis*) to identify which data artefacts and data practices really matter to people (*generative data*), and then move to critical reflection for identifying "*limit-situations*", which consist of socio-ecological relationships that lead to unjust, unsustainable and/or inequitable development trajectories. Based on this, our approach seeks to co-produce "*feasible unseens*" as outcomes that are capable to unveil *data-enabled transformation pathways*. Drawing simultaneously on concepts of data justice (Hoefsloot et al., 2022; Milan and Treré, 2019; Taylor, 2017) and climate justice through equitable transformation and climate-resilient pathways (Bilsky et al., 2022; Henrique and Tschakert, 2021; Leach et al., 2018; Schipper et al., 2022), we conceptualise *data-enabled transformation pathways* as trajectories that leverage data innovations to enact changes in policy and practice towards ensuring more just, equitable and ecologically safe futures. Within our approach (Fig. 1), data-enabled transformation pathways entail new, transformative data practices, innovative digital artefacts, and transformed data futures. The spiral shape of Fig. 1 indicates that the approach is iterative, and the 'feasible unseens' revealed in a given cycle will influence future situational analyses.

3. Methodological interventions for data-enabled transformation pathways

This section describes the main methodological interventions achieved within the "Waterproofing Data" project building upon our dialogic approach (Fig. 1). The project co-investigated the transformative potential of data innovations to improve flood resilience, with study sites across three scales in Brazil (communities, local governments, national centres of expertise). We employed a combination of several methods and digital tools, so the complete description of the various activities is beyond the scope of this article, but an overview of the main

[1] In the original in Portuguese, Freire uses the term "inédito viável", which has been translated in English as "untested feasibility", a translation which we believe does not capture the novel and transformative aspects of the original and which apparently Freire himself was not comfortable with (Guilherme, 2017).

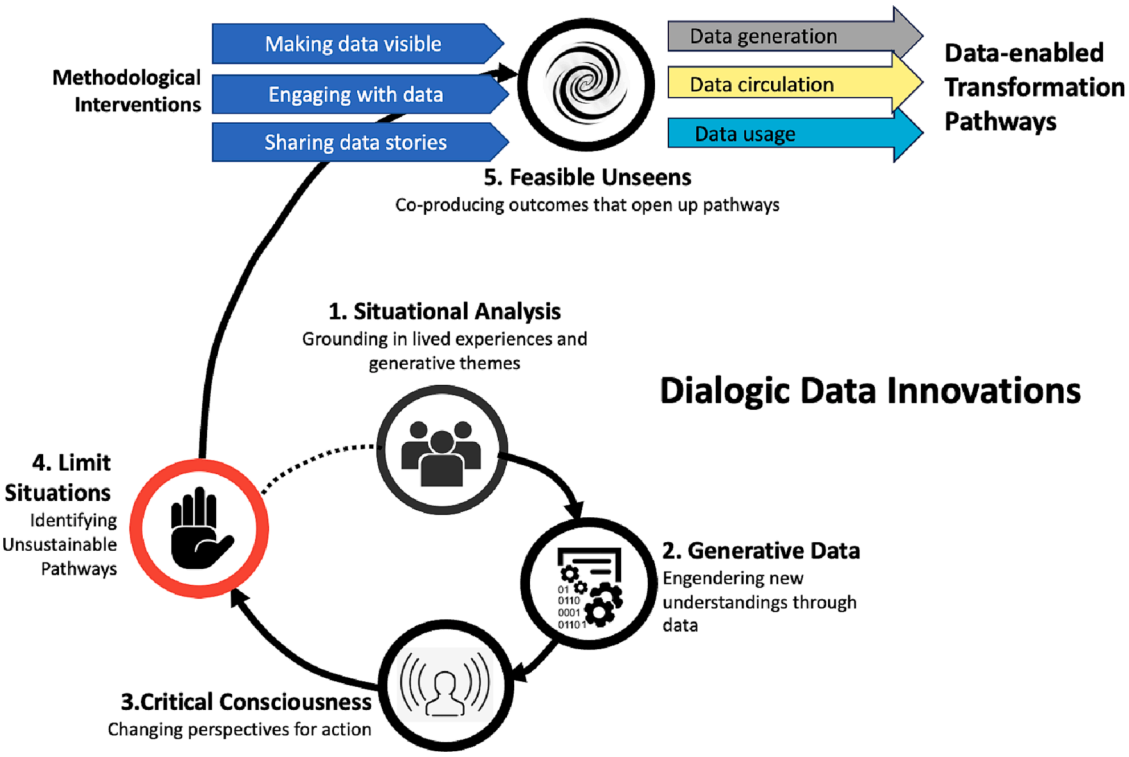

Fig. 1. Schematic diagram of our approach to co-produce data innovations for transformations to sustainability based on the dialogic pedagogy of Paulo Freire.

components, methods, empirical sites, and participants can be found in the Supplementary Material (Table A1), alongside the description of the analysis methods used for the results presented here. The following sections describe the three main methodological interventions and data innovations that emerged from our project activities.

3.1. *Making data visible: From data inventories to data diaries*

The first methodological intervention sought in the project is related to making visible the existing flows of data between citizens, local government authorities, and other agencies involved in the management of water-related risks. For us, the act of "making visible" was an attempt to gain an in-depth understanding of the datasets and data practices related to flooding in concrete settings. Drawing on ethnographic research, we proposed the creation of "data diaries" (Tkacz et al., 2021) as a methodological orientation to produce an account of data and data practices.

The main methodological shift operated by the data diary is to move away from dominant forms of portraying data such as data inventories (e.g., lists of datasets and their link to formal decision-making organisational processes), to a thick description of the informal, day-to-day interactions between people, roles, datasets, physical devices, etc. This was done through ethnographic observations in the situation rooms of two partner flood monitoring centres that are fully reported in (Tkacz et al., 2021), and resulted in a situational analysis (Fig. 1) with textual descriptions and visual diagrams (Fig. 2) that sought to reproduce diverse ways of seeing and knowing data.

The knowledge on data practices captured by the researchers in the data diaries was discussed in two focus group workshops which included each around 15 stakeholders involved in flood risk management and monitoring (details in the Supplementary Material). These workshops were named "Convers(action) Rounds," since their goal was to foster conversations leading to actions, inspired by Freirean "culture circles" (Freire, 2000). Following the dialogic approach of Fig. 1, each workshop started with a presentation of the visual diagrams of the data diary (Fig. 2) alongside other research outputs (e.g., flood memory videos), followed by a discussion with participants aimed at "de-coding" the knowledge synthesised in the data diaries alongside other research outputs. Lastly, researchers and stakeholders sought to identify issues with current practices and co-produce proposals of new data-enabled transformation pathways (as "feasible unseens"), which are reported in Section 4. Re-situating the knowledge captured in this dialogic way entailed a methodological shift: data diaries became an instrument to reveal underlying "limit situations" that served as an invitation to reflection and proposals of transformative action (see Section 4).

3.2. *Engaging with data: From data gathering to data gardening*

Our second methodological intervention has sought to *engage citizens to produce, circulate and embed data to increase flood resilience*. Here, citizen engagement sought to move away from data collection processes in which citizens are invited to act one-directionally as "data providers" for filling data gaps which they did not take part in defining nor can relate to. Instead, we proposed to see data generation practices as being potentially transformative themselves (Porto de Albuquerque and Albino de Almeida, 2020), an approach that entailed a move away from an instrumental "data gathering" towards "data gardening" (Lima-Silva et al., forthcoming). The gardening metaphor signals an important methodological shift to emphasise the need of nurturing and cultivating social practices which not only generate data but also empower participants to transformative social learning. Data gardening embeds citizen data generation within our dialogic approach (Fig. 1) as a means to developing critical consciousness and seeking more complex ways of engaging with flooding events that defy victimhood/empowerment dichotomies (Calvillo et al., 2022) to amplify the voices and worldviews of flood-prone communities in data and in the search for transformation pathways.

"Data gardening" for us consisted of working closely with our partner communities in disadvantaged neighbourhoods in Rio Branco (State of Acre) and São Paulo to co-produce new understandings of flooding, whilst generating new data to bring to light their own ways of experiencing and perceiving floods by incorporating flood memories,

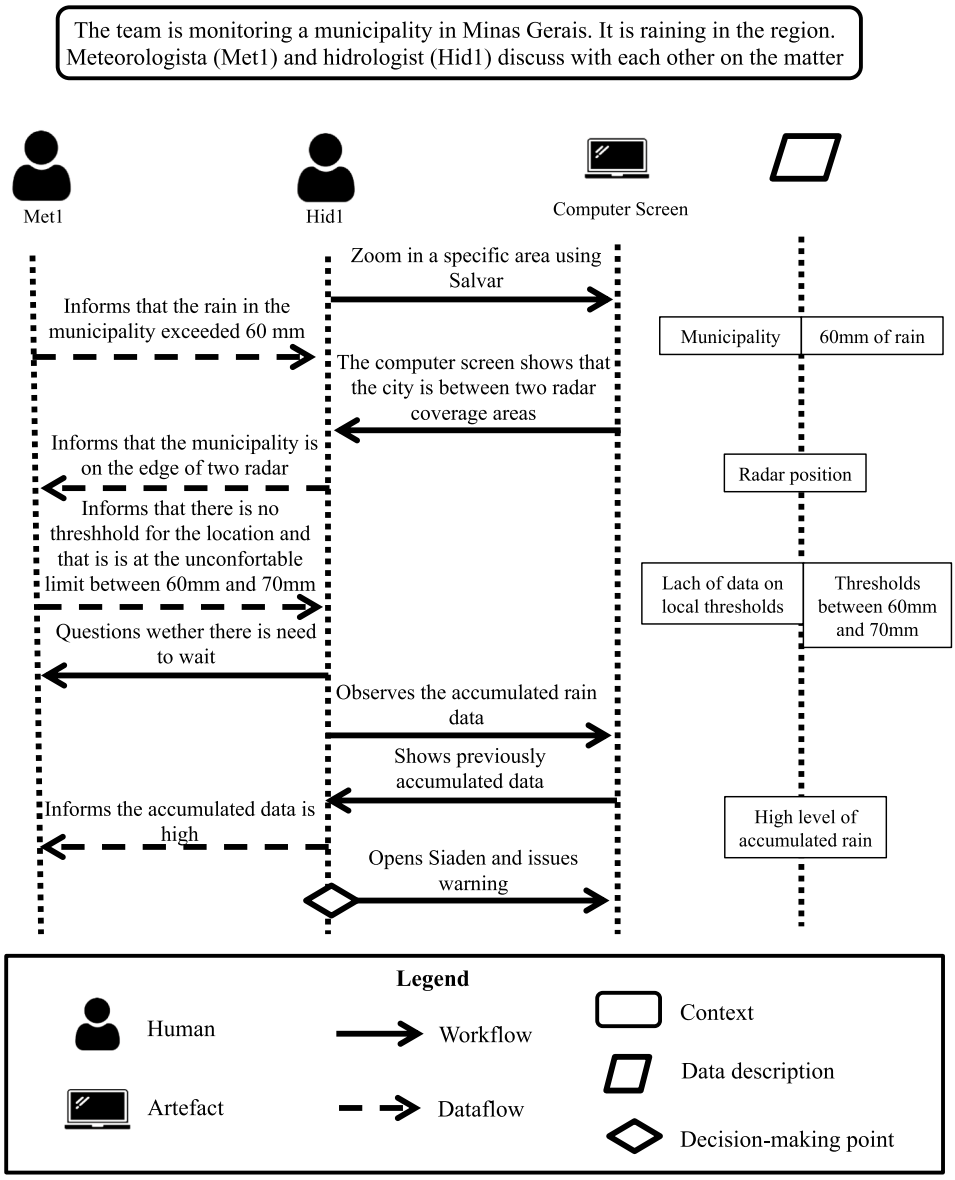

Fig. 2. One representative element of a data diary: a sequence diagram of a data practice in a flood monitoring control room. The icons on the top represent different organisational roles (Met1, Hid1), alongside technology devices such as the computer screen and the video wall. The arrows represent interactions between the corresponding roles within the observed data practice. In the example, two monitoring professionals interact with each other and with several data sources to assess the severity of a rainfall situation. ().
Source: Tkacz et al., 2021

narratives and local/lay knowledge and storytelling. This involved a methodological shift from mainstream flood citizen science, solely focused on hydrological variables to a combination of different methods from the humanities and social sciences to be able to speak to different audiences and intergenerational groups in the neighbourhoods: digital flood memories, participatory mapping, collaborative risk perception mapping, citizen science with schools and data-driven exhibitions (see Fig. 3).

However, right in the middle of our project, the coronavirus rapidly spread and in our case study areas, a teachers' strike was compounded by lockdowns, food insecurity and unemployment. This has required flexibility and the use of virtual engagements, which included developing a school optional module on flood risk and data production, short documentaries, and memory contests. These activities are reported in detail elsewhere (Calvillo et al., 2022) and engaged more than 310 students and 200 community members. Following our dialogic approach (Fig. 1), the data they produced was used in reflection processes that triggered critical and heated debates on their relevance and proposals of their potential usage for leveraging transformations towards flood resilience (reported in Section 4).

3.3. Sharing data stories: From dissemination to pollination, from data integration to diffraction

Our third methodological intervention sought *to integrate citizen-generated data with other data sources to support decision-making and policymaking on flooding.* To accomplish this objective, we designed new software for data generation and visualisation by combining agile software development, participatory software design and the principles of Freire's dialogic pedagogy. This included a methodological shift that re-situated the process of "software requirement elicitation" as part of Freirean dialogic engagements with the software end-users including community members, government stakeholders, flood risk agencies, and researchers from various disciplines. The engagements in "data gardening" activities (discussed in the previous section) led to a new software tool to support participatory mapping: the "Sketch Map Tool" was developed by our team for enabling community members to easily draw the areas of perceived flood risk, which can be digitised by researchers as geographic data (Klonner et al., 2021).

The dialogic engagements of initial project activities have also led to a new mobile app to enable citizens not only to generate flood data but also to have access to official data about their neighbourhood (e.g., flood

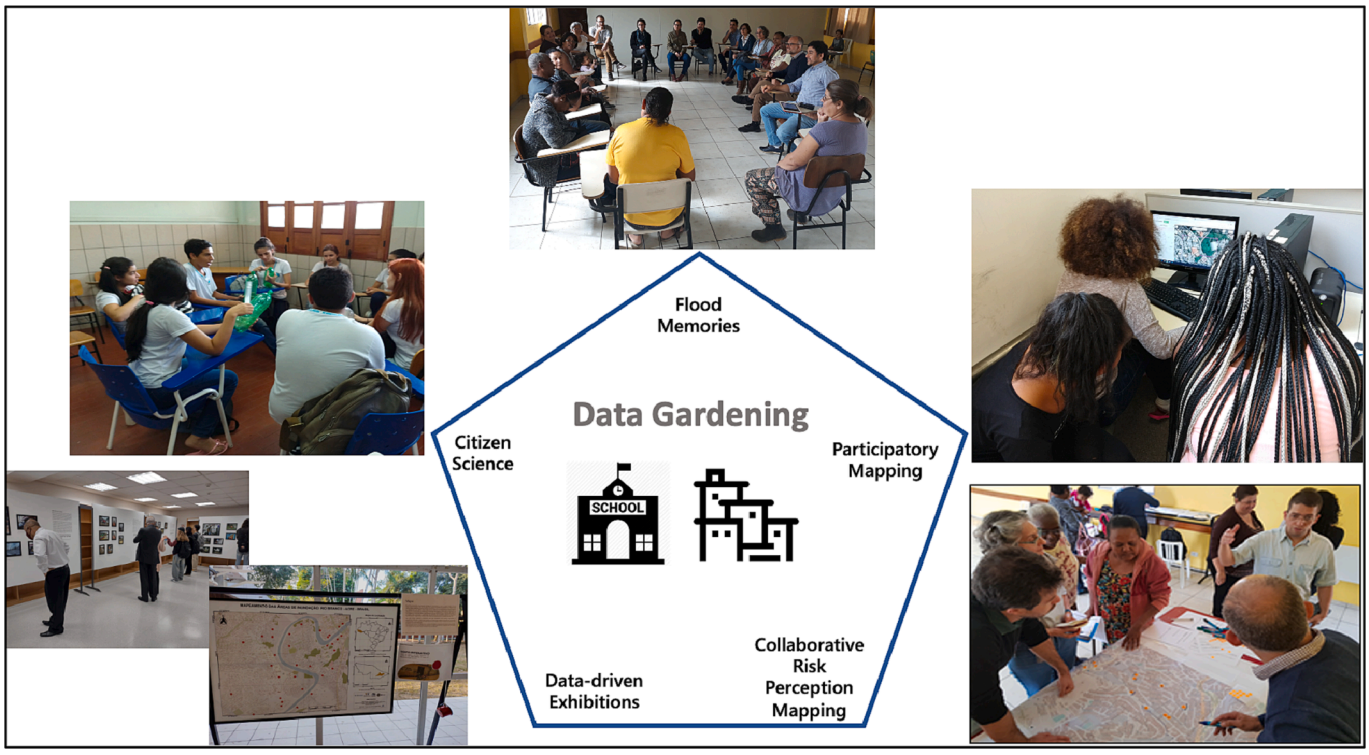

Fig. 3. Diagram representing the various data collection strategies used in our "data gardening" methodology (from top to right): (a) flood memory circles with elderly citizens in M'Boi Mirim, São Paulo; (b) school students in M'Boi Mirim use OpenStreetMap for collaborative mapping of their neighbourhood; (c) researchers and residents of a flood-prone area in São Paulo use a sketch map to draw on areas of perceived flood risk; (d) data-driven exhibitions present photos, stories and maps generated in the project to the public; (e) school students of Rio Branco, Acre, building artisanal rain gauges for citizen science activities. Source: project archive.

hazard areas). To support this, focus groups were organised with school students, community residents and flood risk managers for collaborative situational analysis. The collective discussion and critical analysis of those situations aimed to promote critical consciousness whilst also revealing potential transformative pathways which could be supported by the new software (Fig, 1). This led to an open-source mobile app to

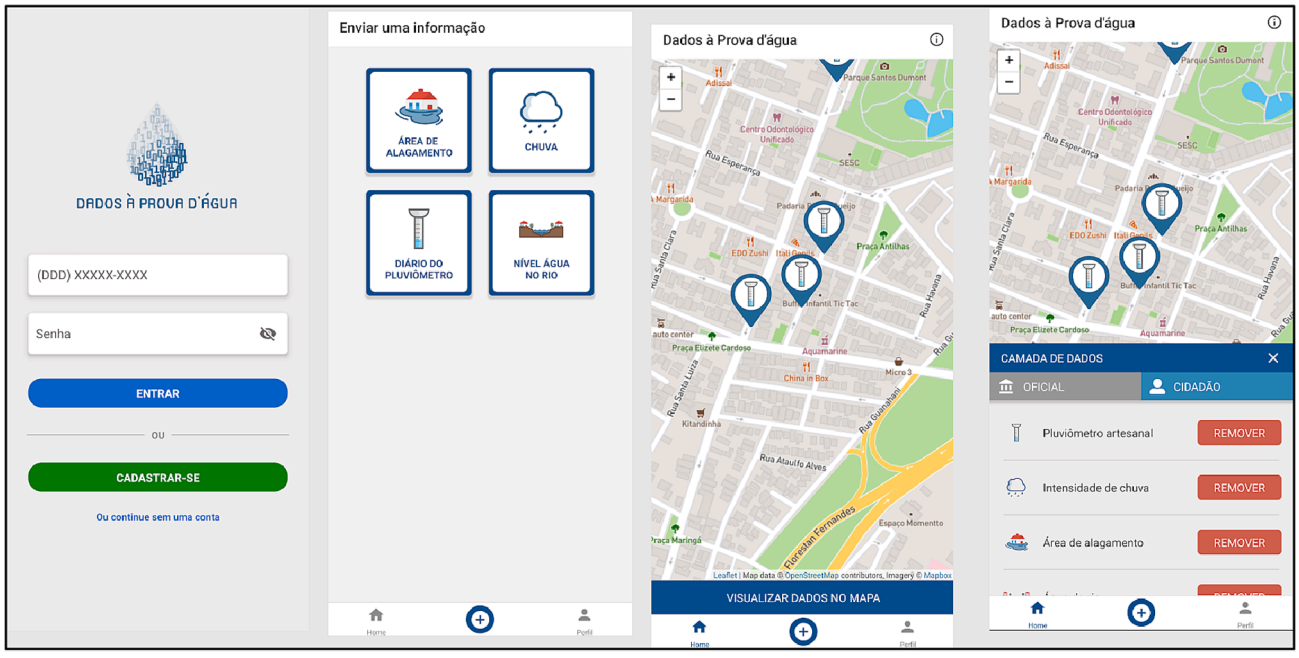

Fig. 4. Screenshots of the Waterproofing Data mobile app (left to right): (a) initial login screen; (b) selection of the types of data that can be generated by citizens: flood area ("área de alagamento"), rain ("chuva"), diary of the rain gauge ("diário do pluviômetro"), river water level ("nível de água do rio"); (c) screen with a map of existing data entries in the neighbourhood; (d) screen with the data layers available: artisanal rain gauges ("pluviômetro artisanal"), rain intensity ("intensidade da chuva"), flood area ("área de alagamento"). Source: from the Waterproofing Data mobile app.

support citizen science on flooding impacts by communities in situations of vulnerability, with a particular focus on school students and civil protection volunteers. With the app, school students become citizen scientists by sharing data about observed rainfall (e.g., measured by self-made rainfall gauges) and the local impacts of flooding (e.g., observed flooded areas and river levels), as depicted in Fig. 4 (details can be found in our Teacher's Guide, see Supplementary Material). By observing the correlations between rainfall measurements and the corresponding impacts in their neighbourhood, they also acquire a critical understanding of the local dynamics of flood risks.

Our dialogic approach meant that the process of reaching out to potential users of the app would also require a methodological shift. This included moving away from a "top-down" process of 'dissemination' to the metaphor of "pollination": in close collaboration with our partners in the Education programme of the National Centre for Disaster Monitoring and Early Warning ("Cemaden Educação"), we engaged local facilitators in schools and municipal civil defences – "the pollinators" – who could help us to spread the seeds we had cultivated in our "data gardens." 21 "pollinators" were seconded to our project activities (15 schoolteachers and 6 civil protection agents), who supported expanding the project activities to nine cities in five different Brazilian states. Since we were in the middle of the COVID-19 pandemic with travel restrictions and safety concerns when the app was released, our "pollinators" attended an online capacity-strengthening programme for four months, covering core concepts of citizen science and flooding. They undertook three interdependent activities: (a) engagement of school students and community volunteers in their neighbourhoods for a trial of a mobile app; (b) co-production of a set of guidelines for embedding flood data generation in the school curriculum; and (c) qualitative and quantitative evaluation of the results achieved. Fig. 5 shows the resulting citizen submissions of data using our mobile app, which included more than 6,600 rows of data generated by 318 citizen reporters located in 24 partner schools and 13 civil protection agencies.

A final additional methodological shift concerned "data integration" and the platform for management and visualisation of the flood data generated in the project (Pajarito-Grajales et al., 2022). Since we considered flood data generated by citizens using a variety of methods alongside conventional flood data, it was important to "embrace pluralism" (D'Ignazio and Klein, 2020) by not imposing a single integration schema that flattens out differences in underlying ontological assumptions, worldviews, and potential contradictions. Instead, we drew inspiration from the diffractive approach proposed by Uprichard and Dawney (2019) following the work of feminists Karin Barad and Donna Haraway: the different methods used to generate flood data in our project can be seen as producing different "cuts" to the object (flooding) whose potential contradictions and misalignments may be revealing of important ontological complexities. Seeking to support a wider range of ways of "cutting" floods in data, we used a cloud computing technique called "data lake", which enabled storage of heterogeneous data types (e.g., flood memory videos, citizen rainfall measurements). In terms of visualisation, this approach implied moving from a web portal with one map and several layers for the different data (Fig. 6) to a place-based dashboard which presents various "data stories" (Fig. 7). The place-based visual data stories enable reflection and action through the contrast and complement between the several official and citizen-generated data sources related to floods in each location.

4. Data-enabled transformation pathways

This section reports on the outcomes achieved by our methodological interventions (Section 3) as "feasible unseens" (Section 2) produced by the data practices of data generation, data circulation and data usage. Based on them, we conceptualise six transformative roles of data, which are obtained by relating the observed outcomes to the functions of data identified in our previous work (Porto de Albuquerque et al., 2021) that build upon Roman Jakobson's communication model (1960). This led to the identification of a framework of six data-enabled transformation pathways that can be unlocked by leveraging the transformative roles of data (depicted in Fig. 12).

4.1. Data generation

Pathway 1 – New data are generated to amplify oppressed voices and their plural ways of knowing, making the evidence base more

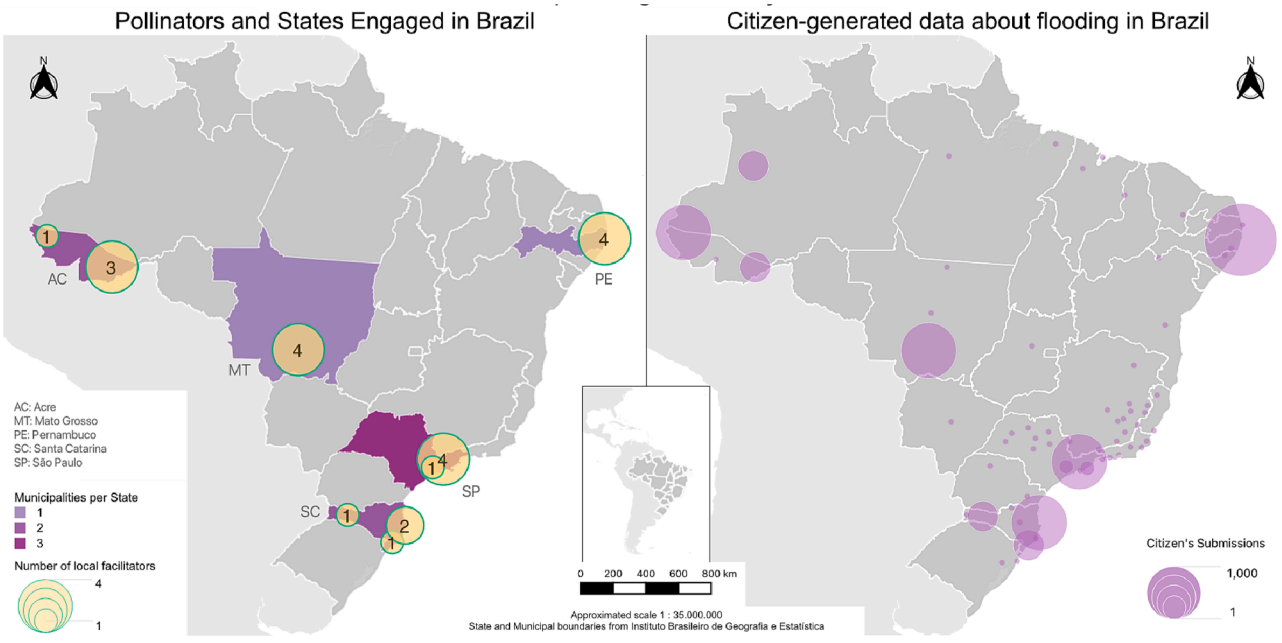

Fig. 5. Maps of Brazil showing the spatial distribution of project activities. Left: locations and number of facilitators "pollinators" who joined the project in each of the five participant Brazilian States. Right: Spatial distribution of the data rows submitted by citizens using the Waterproofing Data mobile app in the period between 1 December 2021 and 30 June 2022. The highest amount of data comes from the locations of the "pollinators" on the left, but the mobile app has also been used to generate data in many other cities and states. Source: authors.

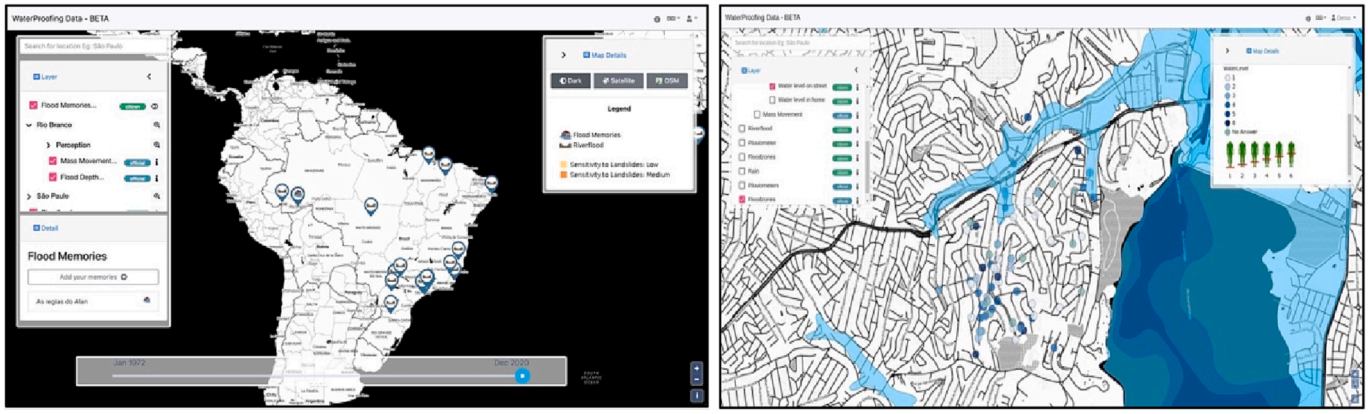

Fig. 6. Screenshots of the first version of the web portal with layers for the several types of citizen-generated data and official data. Left: overall map with the location of data across Brazil; Right: detailed map of a city showing areas indicated by citizens as at flood risk in blue. Source: project archive. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

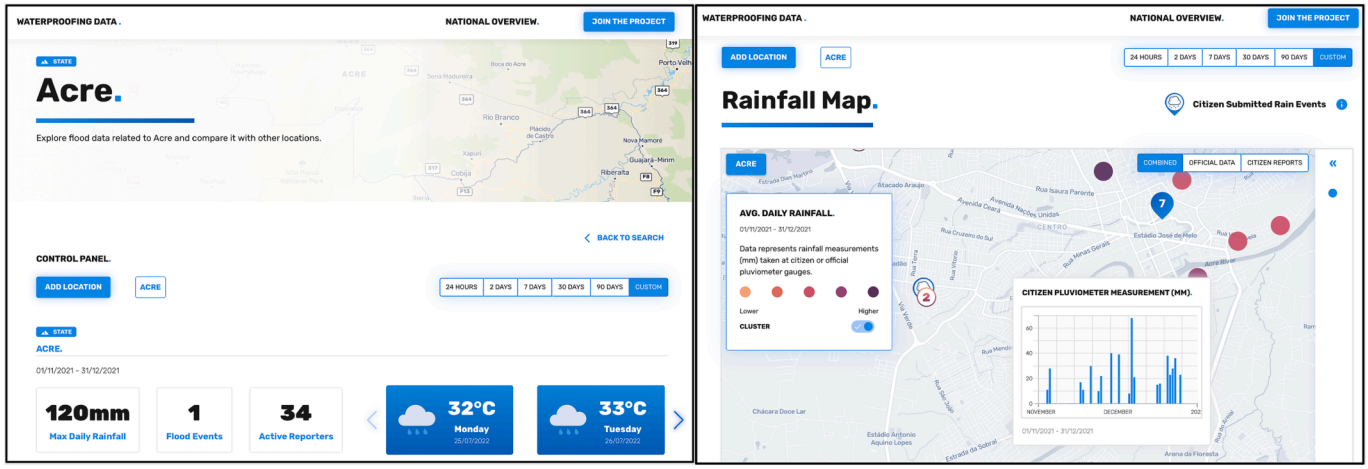

Fig. 7. Screenshots of the Waterproofing Data Dashboard show various perspectives on the data generated by citizens. Left: Initial screen of the Dashboard for the State of Acre; Right: Rainfall map for the same location shows active citizen reporters (dots) - when one of them is selected, a bar chart is presented with the measures recorded over time by their citizen pluviometer (rain gauge). Source: Waterproofing Data Dashboard.

equitable and inclusive.

In our project, school students from vulnerable social groups in São Paulo and Rio Branco experienced the process of making their neighbourhoods and their concerns visible on the digital maps of OpenStreetMap. These activities helped democratise flood data generation by including oppressed voices on the digital map such as those of visually impaired people, the elderly, and young people from vulnerable areas.

Another outcome associated with this transformation pathway came from using citizen-generated data to expand the perspectives on *what* counts as "flood data", *who* counts as a data producer and *to whom* flood data is addressed. This was achieved through our methodological interventions that complemented the traditional sources of flood data dominated by the natural sciences (e.g., rainfall gauges, water river gauges, satellite imagery etc.) with a wider range of data types, including rainfall measured with artisanal gauges from plastic bottles, sketch maps of community risk perception, alongside flood memory videos with personal stories and lived experiences of flooding. This outcome was reflected in a statement by one director of a flood monitoring agency that our project helped her to realise the importance for those who come from the "hard sciences" (like her) to "*introduce the social sciences, the society within this complex package which is disasters […] since only the combination of scientific knowledge with the popular wisdom and local knowledge about the place-based dynamics of phenomena will lead to more resilient cities*".

These outcomes point to a transformation pathway revealed by supplementing the conventional event/hazard-centric measurements of flood risk models (Chmutina et al., 2021; Steger et al., 2021) to broaden the perspective on what counts as data towards more plural ways of knowing floods with data, making them speak to the lived experiences and realities of the various stakeholders involved in flood management, including the people living in flood-prone areas. This pathway is related to an *expressive* capacity of data for **filling evidence gaps**: data generation can be an *expressive* medium to empower hitherto "invisible" and oppressed social groups to voice their personal and collective emotive connections to socio-ecological phenomena. When these voices are amplified in data, they not only contribute to filling the data gaps and making the current evidence base more equitable and inclusive but also enable a transformation pathway by promoting more plural ways of knowing socio-ecological phenomena.

Pathway 2 – Rethinking how data are related to socio-ecological phenomena and lived experiences enables challenging unjust, unsustainable development trajectories.

When we started our "data gardening" activities with residents of the impoverished M'Boi Mirim district in São Paulo, the community co-researchers perceived the problems which they frequently experience as a consequence of heavy rains as "given" and not related to floods. By further discussing this, we understood that flood media reports are often biased towards central areas of the city and large-scale catastrophes,

whilst the day-to-day impacts of the "flash floods" of the lived experiences of our community partners were not recognised as floods as they saw "portrayed in the media". As we registered their flood memories, which dated back from the establishment of the neighbourhood as an unplanned urban expansion within a flood plain area, they gained a new critical understanding of how their lived experiences were related to the broader governance of flood risks and early warning systems. This culminated in a community member stating that: "[Flooding] is a very critical case [here], but we did not have this vision of our neighbourhood". During our workshops, community residents discussed two key points: (a) a critical understanding that impoverished urban areas are not situated in flood-prone areas "by chance", but as the result of unjust urban development patterns that are root causes for disaster risks and current climate injustice; (b) a critical appraisal how current data and mainstream representations of floods are (or not) related to lived experiences and local ways of knowing floods.

We gathered further quantitative evidence of improvement of knowledge about floods through an evaluation survey with school students and community resident volunteers after our data generation activities using the mobile app (see details in the Supplementary Material). Fig. 8 presents results which indicate the positive impact of data generation activities on the flood risk knowledge of participants.

The changes in perspective and increased flood risk knowledge are only initial small steps towards climate-resilient trajectories. However, they unlock a transformation pathway that can be enacted not only by follow-on community-based risk reduction but also by residents now being able to advocate for pro-equity public policies and interventions to reduce flood risks in their neighbourhoods. These outcomes leverage data generation **for developing critical consciousness**, affording reflection and critical analyses of the "status quo" to enable transformations. In addition to the outcomes arising from making sense of the data achieved by these activities (discussed later), the act of generating data *per se* bears a transformative potential through a *metalingual function* (Porto de Albuquerque et al. 2021). By engaging in data generation, citizens are empowered to rethink how socio-ecological phenomena and their lived experiences are represented in existing data (or not). This opens up a transformation pathway as it enables them to review and challenge current unjust and oppressive relationships between people and the environment, as well as the unsustainable development trajectories they lead to.

4.2. Data circulation

Pathway 3 – Data flows establish new communication channels to facilitate collective action and democratise the governance of socio-ecological relationships.

Our project collected evidence that the data circulation practices have contributed to establishing new communication channels between the residents and local government officials. One participant in our evaluation workshop noted that our mobile app enabled "*a dialogue between the community and public organisations of the national system of civil defence and protection*".

We collected further evidence that the practices of data circulation have enlarged the flood resilience network by engaging a more diverse set of social actors. In Santa Catarina State, the data generation methods developed in our project began to be applied for the 2022 school year reaching all state schools partnering in the Civil Defence and enabling the establishment of new volunteer groups with residents of flood-prone areas. This contributed to making the governance of flood risks more inclusive by creating new place-based connections that laid the foundation for collective transformative action involving diverse social groups such as civil defence agencies, residents of flood-prone areas, local government, and universities.

The transformative potential of these outcomes leverages data circulation for **enabling connections**: the flow of data creates and maintains communication channels that allow recognition and communication between different social groups. This opens up a pathway to widen the stakeholders and perspectives active in the governance of socio-ecological relationships to make it more democratic, inclusive and equitable.

Pathway 4 – Marginalised actors engage in data exchanges to make the governance of socio-ecological relationships more inclusive and equitable.

In our project, we identified outcomes associated with a behavioural change of participants from apathy to an engaged praxis (i.e., combined reflection and action). Following our several cycles of interaction with communities within "data gardening", adults, students, and some groups usually considered unlikely to contribute, such as the elderly or people with visual impairment, were actively engaged in data generation and actively contributed to the monitoring activities. By specifically addressing these social groups with our data practices, recognising them and incorporating their inputs into the new data flows enabled by our

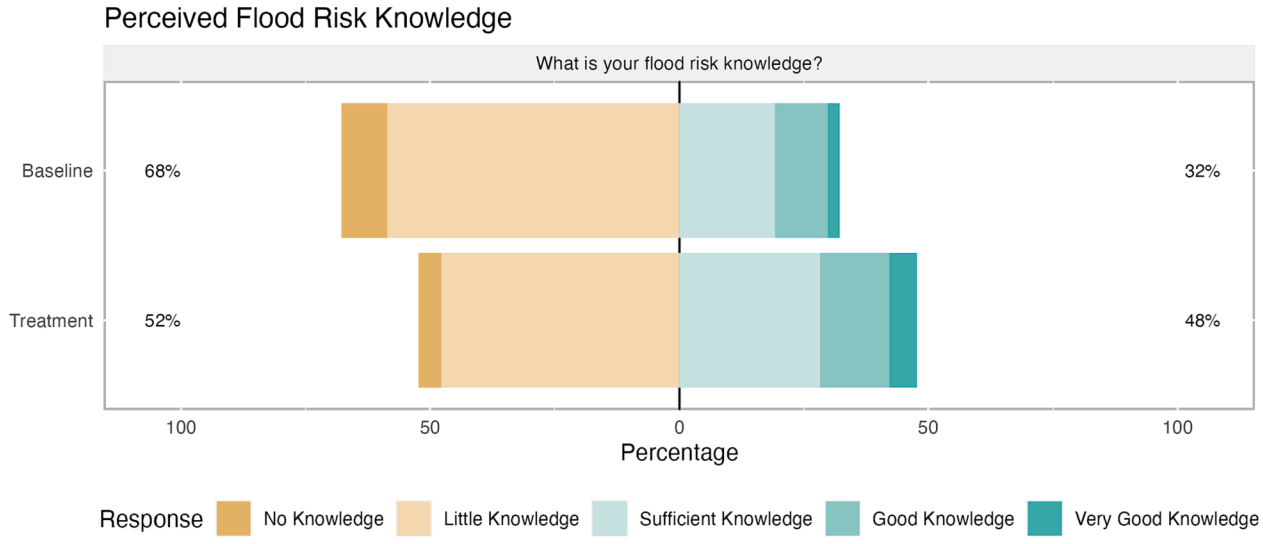

Fig. 8. Perceived flood risk knowledge, visualisation of the results of a survey with the group of users before (baseline, n = 292) and after they participated in data generation activities (treatment, n = 216). The percentage of participants who declared to have "sufficient", "good" or "very good" flood risk knowledge after our pedagogical intervention (48%) was higher than before their participation (32%) and this difference was statistically significant (Wilcoxon Signed Ranks Test, $p < 0.0005$, effect size, $r = 0.324$). No significant change has been observed in a control group of non-participants. Source: authors.

mobile app, our community co-researchers reported increased confidence and resources to advocate for their rights and play a more active role in flood governance. This was the case of an informal settlement leader who after participating in our project activities, presented the flood risk maps they produced in the community to local government agents to actively advocate for action from formal decision-makers.

Another related outcome was evidenced when the Civil Defence of Mato Grosso state worked with the city mayor about an area of persistent flooding using data generated in our project using a self-made rainfall gauge. They used these data as evidence that the flood was not due to surface waters but to the overflow of the channelled river. As a result, "*the City Hall started to use this information and will start remediation works, after saving several thousand [Brazilian] reais that they would have paid for a study in the flood-prone areas*" (Civil Protection Agent). In this case, citizen-generated data has been used to hold local governments to account and demand action, a significant outcome that democratises the governance of flood risks by shifting the traditional bases of production, ownership, and centralization of data and knowledge about floods.

These outcomes point to a transformation pathway that builds upon the capacity of data exchanges for **mobilising to action**, i.e., the circulation of data can address a specific social actor and engage them for transformative action. It corresponds to Jakobson's "conactive" language function (Porto de Albuquerque et al., 2021).

4.3. Data usage

Pathway 5 – Aesthetic affordances of data are artistically explored to transform perspectives and behaviours.

Our research team received a poem ("Cordel") written by a citizen from the city og Jaboatão dos Guararapes, describing the data practices in which they participated. Cordel is a popular literary genre, often written rhymingly, originating from oral accounts and later printed in pamphlets. Another related outcome came through our data-driven art exhibitions (Fig. 9) with panels exhibiting texts and photographs of flood memories, enabling a wider public to have access to lived experiences of flooding in our partner communities. At the same time, people were invited to engage in data generation in the exhibition through a map to which they could add stickers to mark the places of flood events they have experienced themselves. These forms of artistic rendering of project results invited new emotional connections and new imaginaries to rethink relationships with the people and phenomena of flooding, thus unfolding a pathway to solidary transformative action.

These outcomes concern an underemphasised potential: data and data practices can be used with a *poetic* function for **resignifying socio-ecologies**, i.e., their aesthetic affordances can be explored in new artistic ways to represent current and future relationships between people and environment, motivating to transform perspectives and behaviours through engagement and action.

Pathway 6 - Improved data support more inclusive, evidence-informed decision making and empower a wider range of social actors to transformative actions.

During our project, further evidence of outcomes associated with data usage came during the rainy season of 2021, when the Amazon region suffered major floods, especially in the State of Acre. We supported a group of local students to organise volunteers from around the world and complete the maps of nine cities affected by flooding using OpenStreetMap. Fig. 10 shows the map of Rio Branco before and after these activities, revealing a much more detailed picture of buildings, schools, and other critical infrastructure of the cities which were exposed to flooding. The Secretary of the State Government of Acre incorporated these maps into the government dashboard created to manage the emergency and reported that these citizen-generated data have been very useful in the flood response to assess exposure to floods in a more inclusive way.

In addition to informing the government, our project has collected evidence that the availability of data has also been used to inform decision-making in the everyday life of citizens living in flood-risk areas. The most significant related outcome happened after the catastrophic heavy rainfall events in May 2022 across the North-eastern region of Brazil which displaced at least 25,000 people and caused 133 deaths (Climate change increased heavy rainfall, hitting vulnerable communities in Eastern Northeast Brazil, 2022; Marengo et al., 2023). The Metropolitan Region of Recife in Pernambuco state – Paulo Freire's state of birth – was severely affected, with impacts concentrated in low-income neighbourhoods. Among them, the city of Jaboatão dos Guararapes, one of the most active sites in our "pollination" activities, was severely hit and concentrated half of the overall death toll. Screenshots from our dashboard (Fig. 11) show that citizen scientists systematically recorded the daily rainfall using our mobile app, recording a peak of 150 mm on 25 May 2022 and raising a citizen alert: "*Area with flooding, due to the increase in millimetres of rain. Alert situation*".

The civil defence coordinator later explained that the young citizen scientists were aware of the imminent threat of floods because they had participated in our project activities before. They could correctly interpret the high rainfall volumes recorded and take early actions of

Fig. 9. A general view of the Waterproofing Data exhibition in Acre (left-hand side) and detail of the interactive panel with a participatory map of flood events (right-hand side). Source: project archive (with permission).

Fig. 10. Example of OpenStreetMap base map of Rio Branco before mapping activities (left-hand side, March 2020) and after the research (right-hand side, June 2022). Source: project archive and (Klonner et al., 2022).

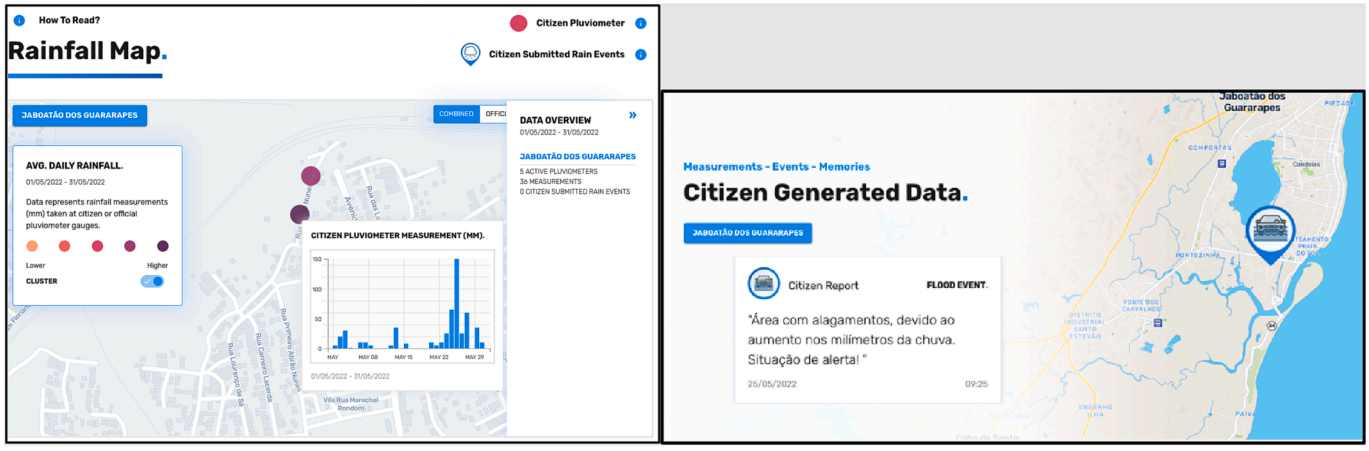

Fig. 11. Average rainfall recorded by a citizen on the app (left-hand side using our mobile app and their self-made rain gauge, reaching 150 mm on 25 May 2022, which prompted a citizen reporter to record a warning (right-hand side). Source: Waterproofing Data Dashboard.

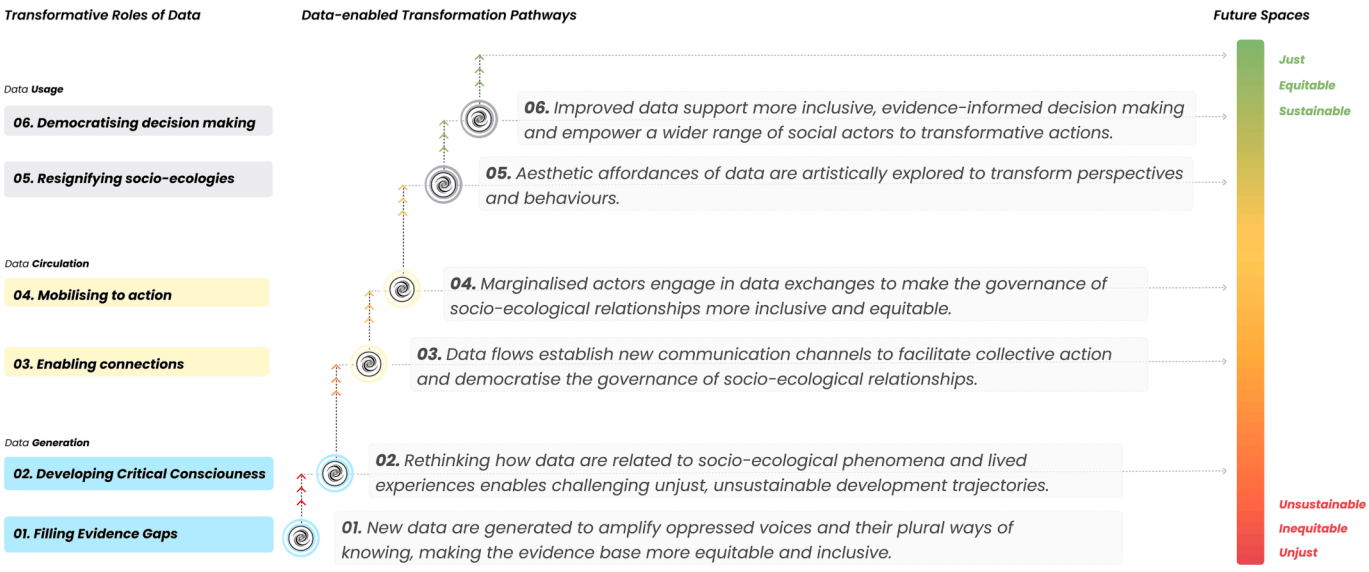

Fig. 12. Schematic diagram of the data-enabled transformation pathways framework.

self-protection, orienting other community members to relocate to safer grounds. Despite the severe damage to their houses, no deaths were registered in these communities, in sharp contrast with the several fatalities in neighbouring areas. This outcome points to a powerful pathway opened by democratising decision making, which enabled citizens living in flood-prone areas to make sense of data to turn warnings into early action and thus save lives.

The final pathway revealed by our work leverages the perhaps most visible role of data: providing referential (indexical) access to socio-ecological phenomena to support decision making. However, we connect this role with a normative aspiration of **democratising decision-making** in two ways. First, data innovations can improve the evidence base to inform more inclusive decision-making related to socio-ecological risks. Second, data innovations can also democratise decision-making by enlarging the range of data end-users, empowering a wider variety of social actors to take evidence-informed and transformative actions.

5. Discussion: Processes and pathways of transformations to sustainability

This article makes two main contributions discussed as follows.

5.1. Processes: A dialogic approach for the co-production of data innovations

From our transdisciplinary work, we derived the concept of *dialogic data innovations* (Section 2) as a methodological approach for co-producing data innovations through methodological interventions (Section 3), drawing on the dialogic pedagogy of Paulo Freire (Freire, 2000). Freire's approach is intrinsically connected to deliberate social change and has thus much to offer for the research and practice of sustainability transformations. As argued by previous studies (Pelling, 2010; Vogel and O'Brien, 2022), Freire's warning about the uncritical "adaptation" of the oppressed to their oppressive circumstances is crucially important for research on and for social change. We have shown how these principles can be made productive to overcome the uncritical stance criticised by Freire and enable methodological interventions towards transformative climate adaptation initiatives.

Our approach includes the dialogic engagement not only of oppressed people but also of other societal/institutional actors and researchers who are involved in the transdisciplinary co-production of sustainability transformations, building on previous studies that emphasised the value of transdisciplinarity for transformative change (Moser, 2016; Shrivastava et al., 2020; Vogel and O'Brien, 2022) and of transforming "from below" (Mehta et al., 2021). Nevertheless, in doing so, it is crucially important to acknowledge the power and epistemic asymmetries that exist between hegemonic societal actors and oppressed persons living in conditions of vulnerability. This necessitates paying careful attention to the ontological perspectives and worldviews embedded in data and digital technologies (Porto de Albuquerque et al., 2013) and the "constitutive tensions" that emerge in engaging oppressed people in data generation (Porto de Albuquerque et al., 2021; Porto de Albuquerque and Albino de Almeida, 2020). Future works will need to examine further the politics and complexity of how data innovations interact with the ontological worldviews of local/subaltern knowledge (Klenk et al., 2017; Lam et al., 2020; Olazabal et al., 2021), especially when they conflict with the mainstream narratives embedded in official data or when the visibility of local conditions through data could lead to negative implications for residents.

5.2. Pathways: A framework for data-enabled and climate-resilient transformation pathways

Our dialogical methodological approach to data innovations has opened co-produced data-enabled sustainability transformation pathways (Section 4), which together can shift the solution spaces of climate adaptation and development trajectories towards more just and equitable, climate-resilient futures, as depicted in Fig. 12. What emerges from our work is a framework that conceptualises the ways with which data innovations can contribute to sustainability transformations. Our conceptual framework identifies six transformative roles of data (left-hand side of Fig. 12) related to the practices of generating, circulating and using data. Data innovations should leverage these transformative roles to achieve "feasible unseens" (circles in Fig. 12), i.e., outcomes that are capable to create inflexion points that steer away from current undesirable development trajectories by unlocking data-enabled transformation pathways (centre of the diagram in Fig. 12). Combining and further cultivating these transformation pathways will enable progress towards more just, equitable and sustainable future spaces (right-hand side of Fig. 12).

Therefore, the resulting data-enabled transformation pathways are "solution-oriented trajectories that are charted from today's world to achieve desirable climate futures" (Henrique and Tschakert, 2021, p. 3). They can be used alongside the corresponding transformative roles of data as heuristic devices for future research, policy and practice to design and evaluate data innovations as regards their capability to enable just transformations to sustainability. This conceptual framework paves the way for leveraging the power of data innovations in climate adaptation towards shaping future development trajectories that are not only ecologically safe within planetary boundaries, but also explicitly incorporate normative values of equity, inclusion, and justice.

Our conceptual framework is a response to the critical agenda on the roles of data in sustainability transformations (Porto de Albuquerque et al., 2021) and to calls for innovation modes that explicitly support transformation (Leach et al., 2012). It builds upon and extends previous work on sustainability transformation pathways (Chambers et al., 2022; Denton et al., 2014; Gibson et al., 2016; Henrique and Tschakert, 2021; Leach et al., 2018) through the incorporation of Freirean dialogic principles in the transdisciplinary co-production of data innovations to open climate-resilient pathways. In our study, "waterproofing data" meant unlocking transformation pathways that exploit a wider set of roles of data by expanding the types of data considered in flood risk management and engaging diverse social groups in data practices of generation, circulation, and usage to improve flood resilience.

However, the outcomes presented here are only initial steps along a longer-term journey for the transformation pathways revealed. Ensuring long-lasting transformation towards just and sustainable futures is a much larger task than a three-year research project could achieve; it requires that the pathways unlocked with our framework are further enacted and cultivated towards sustained change (J. M. Chambers et al., 2022). How to navigate power asymmetries and the influence of existing social structures and hierarchies in the cultivation of these data-enabled pathways are important issues that will need to be investigated by future research.

6. Conclusion

Urban data solutions that are truly transformative must not only encompass the development and deployment of novel digital technologies but also the co-production of new understandings, perspectives, social practices, and transformed governance arrangements. Inspired by a Freirean approach, our results emphasise the importance of developing methodological interventions that combine data analytics methods and tools with a wider range of participatory methods towards a new form of *participatory urban analytics* to enable just and sustainable transformations. We have shown that dialogue can be used as a methodological tool for problematising positions and revealing tensions through methodological interventions, collectively creating new problem spaces and opening up more just, equitable and sustainable solution spaces. We hope that this approach can be useful for further research, policy and practice on data innovations, contributing to the co-

production of future climate-resilient transformation pathways which are truly inclusive, equitable and just.

Open access statement

CRediT authorship contribution statement

João Porto de Albuquerque: Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Visualization, Supervision, Funding acquisition. **Liana Anderson:** Investigation, Writing – review & editing. **Nerea Calvillo:** Investigation, Writing – review & editing. **Massimo Cattino:** Investigation, Writing – review & editing. **Andrew Clarke:** Investigation, Writing – review & editing. **Maria Alexandra Cunha:** Investigation, Project administration, Funding acquisition, Writing – original draft, Writing – review & editing. **Joanne Garde-Hansen:** Investigation, Writing – review & editing. **Carolin Klonner:** Investigation, Writing – review & editing. **Fernanda Lima-Silva:** Investigation, Writing – review & editing. **Victor Marchezini:** Investigation, Writing – review & editing. **Mario Henrique da Mata Martins:** Investigation, Writing – review & editing. **Diego Pajarito Grajales:** Investigation, Writing – review & editing. **Vangelis Pitidis:** Investigation, Writing – review & editing. **Mohammed Rizwan:** Investigation, Writing – review & editing. **Nathaniel Tkacz:** Investigation, Writing – review & editing. **Rachel Trajber:** Investigation, Writing – review & editing.

Code availability

The source code of all the software tools used in the Waterproofing Data project and reported in this article are openly available in the following repositories:

– Klonner, Carolin, Hartmann, Maximilian, Djami, Lily, Dischl, Rebecca, Reimer, Michelle, Mallmann, Yannik, & Schuchardt, Leonie. (2022). Sketch Map Tool (0.9). Zenodo. https://doi.org/10.5281/zenodo.6985566.

– Livia Castro Degrossi, Daniel Barros, Ana Luiza Figueiredo, Gabriel Trettel, Mohammed Rizwan Khan, & Diego Pajarito Grajales. (2022). Waterproofing Data Platform (v0.1). Zenodo. https://doi.org/10.5281/zenodo.7624744.

– Andy Clarke, Diego Pajarito Grajales, & João Porto de Albuquerque. (2022). Waterproofing Data Dashboard (v0.0.1). Zenodo. https://doi.org/10.5281/zenodo.7624868.

Declaration of Competing Interest

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Data availability

Due to ethical concerns, supporting data cannot be made openly available. Further information about the data and the conditions for access are available to bona fide researchers, subject to registration, from the UK Data Service.

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– Software developers: Ana Luiza Figueiredo, Gabriel Trettel, Bruno Aristimunha, Daniel D'Angelo R. Barros, Jean Neves, Yan Marques.

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Appendix A. Supplementary data

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