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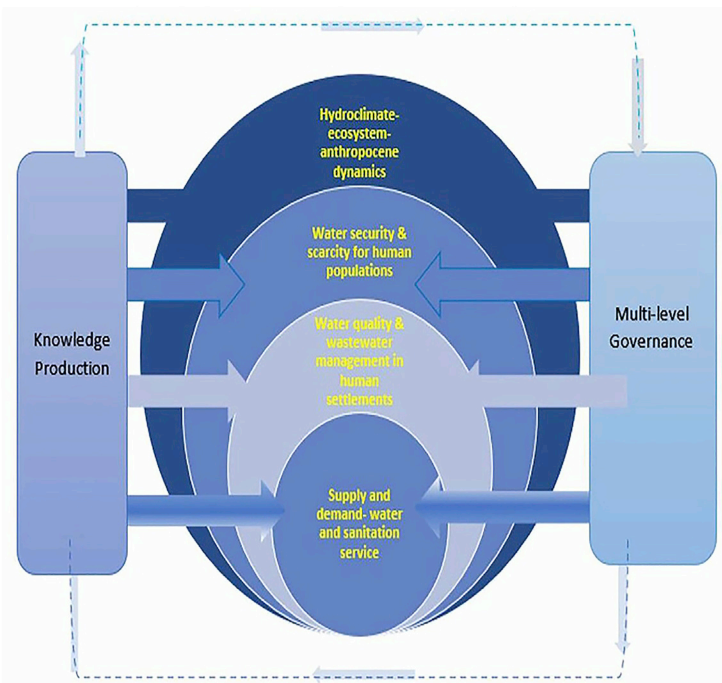
The top 100 global water questions: Results of a scoping exercise

Graphical abstract



Highlights

- We identify 100 priority global water-research questions for the coming decade
- The 100 questions are in six thematic areas connecting the local to the global scale
- Questions about governance and knowledge production cut across all scales
- These questions offer a shared framework for interdisciplinary water research

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In brief

This paper identifies the results of an exercise to identify the 100 important research questions on water for the coming decade. These questions show the importance of water researchers working together, from across different disciplines, to tackle problems of access to water and sanitation at the local level but also to connect local problems to global dynamics of climate and human interactions.

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The top 100 global water questions: Results of a scoping exercise

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SCIENCE FOR SOCIETY Water is a vital resource and is critical for sustainable development. Human survival, energy and food production, and healthy ecosystems are all dependent on water availability. Water security is also impacted by and is at the core of adaptation to climate change. Yet, pressure on freshwater resources is growing, and water stress and water risk are increasing at both the local and global scale. The challenge of water security is therefore complex and requires research and action across multiple levels: from household access to water and sanitation; to managing water safety and risk for human populations and ecosystem health; to working through the political and technical challenges of water scarcity and distribution; to understanding the dynamics of the water cycle and how it is being impacted by climate change. The 100 questions identified by this scoping review offer suggestions for research priorities across these different levels and also provide researchers and funding agencies with a shared language to talk across different disciplines and interests.

SUMMARY

Global water security presents a complex problem for human societies and will become more acute as the impacts of climate change escalate. Water security connects the practical water and sanitation challenges of households to the dynamics of global hydroclimates and ecosystems in the Anthropocene. To ensure the successful deployment of attention and resources, it is necessary to identify the most pressing questions for water research. Here, we present the results of a scoping exercise conducted across the global water sector. More than 400 respondents submitted an excess of 4,000 potential questions. Drawing on expert analysis, we highlight 100 indicative research questions across six thematic domains: water and sanitation for human settlements; water and sanitation safety risk management; water security and scarcity; hydroclimate-ecosystem-Anthropocene dynamics; multi-level governance; and knowledge production. These questions offer an interdisciplinary and multi-scalar framework for guiding the nature and space of water research for the coming decades.

INTRODUCTION

The 2020 United National World Water Development Report describes water as the "medium through which nature and human societies experience the impact of climate change."[1] Extreme inequality in human societies and economic and population growth patterns in combination with the complexity and uncertainty of future climate render human-water interactions as "wicked" problem.[2] A wicked problem is one for which it is impossible to define optimal solutions and which instead

Table 1. Big six themes and thematic water questions

Theme	Thematic research question
Water access for human settlements	What are the characteristics of water supply and sanitation systems that provide sustainable access to clean water and sanitation for all?
Water and sanitation safety and risk management	What are the pathways to improve water and sanitation safety and risk management in human settlements?
Water security and scarcity in human populations	How can the competing demands of different water users be reconciled?
Hydroclimate-ecosystem-Anthropocene dynamics	What are the dynamics and interrelationships between hydrology, ecosystems, and human-induced changes on land, water, biota, and climate?
Multi-level governance	What are the critical challenges for the governance of human interactions with water?
Knowledge production	How can water and sanitation research from multiple disciplines collectively work with governance systems to inform policy and human actions?

requires "tackling" strategies.[3] To manage water in a world that is more turbulent, uncertain, novel, and ambiguous[4] requires actions informed by clear problem definitions and scenarios. Complex multi-scalar future water challenges necessitate bringing disciplines together to understand the interconnected implications for different sectors and components of the world's socio-ecological system. Appropriate strategies should then be better understood and negotiated.[5] Where then should strategic water-research priorities lie in addressing this complex and dynamic space?

The complex nature of global and local water challenges requires an emphasis on evidence-based decision-making in management, governance, and policy-making.[6–8] The process of how empirical evidence informs decision making remains under-explored and is frequently de-politicized.[9] The sustainable development goals (SDGs) (specifically SDG 6: Clean Water and Sanitation) and the explicit recognition of challenges at the water-energy-food nexus[10,11] require new priorities for research to be set to guide evidence-based decision-making processes. Critique of research in the water sector suggests it is often supply driven, where researchers conduct specific research to satisfy clients' and sponsors' short-term needs, at the expense of critical and longer-term issues.[12] However, with limited resources committed to water research, the hegemony and contestation of the forms of knowledge that constitute "water science," and the considerable water challenges predicted for the future,[13–16] there is a recognized need to identify priority current and future questions through collaborative future-oriented methodologies that actively engage policymakers, practitioners, and researchers in their formulation.[17]

Well-packaged and strong evidence-based research is assumed to enable robust and rational decision-making[18] to advance the SDGs and build capacity and coherence among stakeholders.[17] Hence, scoping exercises (i.e. gathering and analyzing evidence from within and across large spatial, organizational, and temporal scales) are a useful mechanism to guide the efforts of all actors in the research and policy space.

Similar exercises have been undertaken to identify priority research agendas for conservation,[19,20] human microbiome,[21] and agriculture.[22] This piece is an extension of Brown et al.'s work,[12] which identified key water-research questions for the UK. Likewise, in South Africa, water experts collaboratively identified 54 key water-research questions that require both current and future consideration by water practitioners.[23] More recently, Setty et al. (2020) employed a global survey of water, sanitation, and hygiene (WaSH) professionals to formulate a research agenda and identify critical professional challenges in the sector.[17] Such processes have the collective goal of addressing current and anticipated water challenges by identifying knowledge gaps, guiding future research planning, and informing the allocation of scarce resources while also facilitating collaborative stakeholder deliberation.[12,19,23]

This paper presents the results of a scoping exercise to identify the most pressing water-research questions for the future. Our starting point was the question what are the top 100 global water-research questions? Drawing on expert analysis, we highlight 100 indicative research questions across six thematic domains: water and sanitation for human settlements; water and sanitation safety risk management; water security and scarcity; hydroclimate-ecosystem-Anthropocene dynamics; multi-level governance; and knowledge production. These questions offer an interdisciplinary and multi-scalar framework for guiding the nature and space of water research for the coming decades.

RESULTS AND DISCUSSION

Survey responses

The survey received 459 individual responses from 81 countries and territories, representing one-third of all United Nations member states, with 325 English responses and 134 responses in Spanish. Countries with the highest number of respondents were, in descending order, the United Kingdom (79), India (71), Spain (31), Colombia (19), Peru (18), Mexico (17), Argentina (15), South Africa (13) and Tanzania (13), representing more than 60% of survey participants (Table S1; Figure S2). 22 survey participants did not indicate their countries. In the dissemination of the survey, an effort was made to encourage responses from academics, government officials, non-governmental organizations, professional bodies, and the private sector and across the widest possible spread of water-related interest areas. There was a higher response from the research and education sector (~45%) compared with government agencies, non-governmental organizations (NGOs), and private practitioners (Table S2). Respondents who indicated "Other" belonged to water-related organizations and sectors such as agriculture, finance and trade organizations, digital technology, cooperatives, community-based organizations (CBOs), and philanthropic organizations. Three individuals did not indicate their affiliated sectors. Table 1 sets out the six overarching themes used to organize the top 100 global water-research questions produced in our scoping exercise. The six themes are organized across four scales that link human settlements to the global

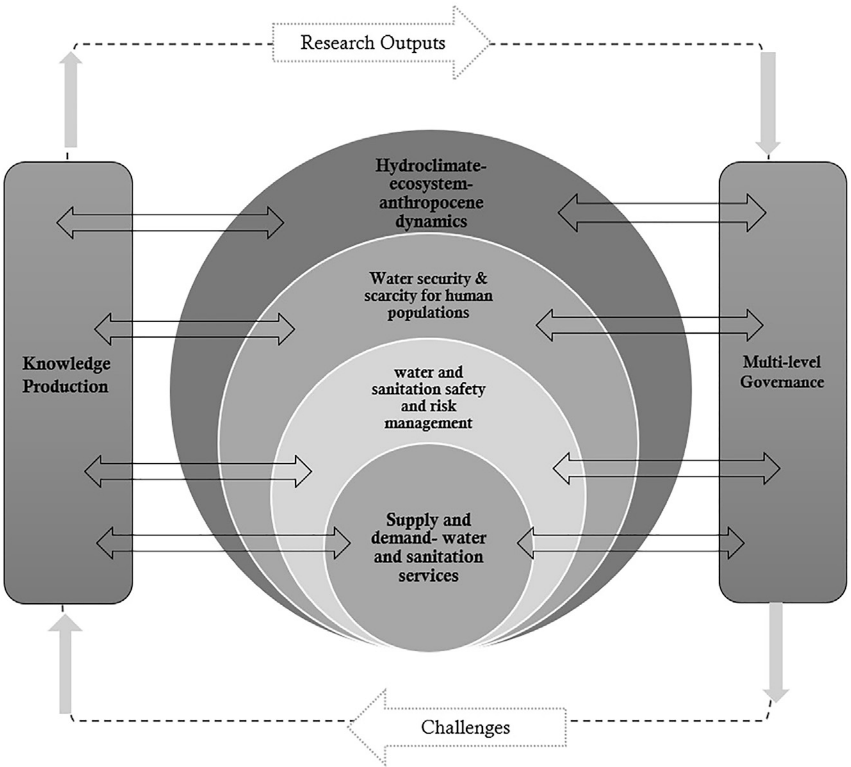

Figure 1. Interscalar relationship between the six big themes

dynamics of the hydroclimate in the Anthropocene. This is represented in Figure 1.

Supply and demand: Water access for human settlements

Thematic question: what are the characteristics of water supply systems that provide sustainable access to clean water and sanitation for all?

The majority of the questions submitted to our survey corresponded to the actual operationalization of delivery, equity, affordability, inclusivity, accessibility, and challenges around providing water and sanitation for all. This primarily concerns the intractable challenges of developing institutional capabilities to deliver effective systems rather than new technologies.[24,25] Our expert-led process identified that the questions grouped under this theme reflected a concern that as global population increases and regions experience disparate demographic and economic transitions in combination with the uncertainties of climate change, the demand for effective management of existing services and the need to invest in new infrastructure and delivery systems will both rise. They anticipated that this has the potential of creating tensions, resulting in competition for scarce water resources and limited sanitation infrastructure at local, national, and global levels. Already, it is estimated that 20% of global groundwater is over exploited, and it is likely that by 2050, more of the world's aquifers will be over exploited.[26] In addition, high-income countries treat about 70% of their domestic and industrial wastewater, whereas this drops to 38%, 28%, and 8% in upper-middle-income, lower-middle-income, and low-income countries, respectively.[27] Therefore, the refined question list in this area suggest that the challenges for water and sanitation delivery are split across concerns over access for all, operational management of systems, economic and technological futures, and responding to the impacts of climate change.

Our scoping exercise identified the following questions (23/100) in this broad thematic area:

Questions associated with water and sanitation for all

1. How will the SDG 6 targets on drinking water and sanitation access be achieved by 2030?
2. How can equitable and affordable water and sanitation services be accessible to all?
3. How realistic is the goal of achieving universal access to a clean water supply and safely managed sanitation under current political and economic conditions?
4. What are the obstacles to the implementation of the human right to water and sanitation in the context of the new public management model of water and sanitation supply?
5. What is the relationship between access to water and sanitation to inequality in all its dimensions (gender, caste, religion, wealth, age, etc.)?

Delivery questions

6. What forms of (appropriate, affordable) safely managed sanitation can be provided in challenging environments (e.g., flood prone areas, atoll islands, informal settlements, etc.)?
7. What technologies/implementation approaches have been successfully and sustainably implemented at scale by government/communities with no "external" (NGO, international agency, etc.) input in the water and sanitation sector?
8. To what extent does concessional funding exacerbate problems associated with weak regulatory frameworks and opportunism associated with infrastructure planning, investment, and asset management?
9. How can the concept of fair tariffs associated with the right to water be applied in rural or informal water and sanitation services?
10. How can regulatory systems be designed to help accelerate investment in and management of longer-term sustainability (financial and resource) goals, particularly if sustainability relies on short-term investments, cross-agency cooperation in investments, and/or more distributed monitoring and compliance requirements that are often too costly for government regulators to enforce?

11. Which economic and non-economic incentives work best at managing sustainable and fair water demand?
12. How can the design of sanitation interventions embed environmental health performance?
13. How can the well-being improvement of people by the provision of safe water and sanitation be measured, capitalized, and included in the cost-benefit analysis of a water supply and sanitation system?

Economic and technological futures

14. What is the possibility of retrofitting existing properties (facilitated by technology/byelaws) to utilize rainwater and graywater for sanitation and gardening to ensure potable water supplies cannot be compromised?
15. What are the challenges of implementing universal water metering and efficient pro-poor water pricing across sectors for promoting water conservation and efficiency?
16. What is the viability of using water transfers and artificial recharge to strategically sustain aquifers?
17. What are some of the most efficient ways of large-scale as well as local-scale water sequestration, and how can these be incorporated or retrofitted into mainstream urban planning?
18. How can effective environmental solutions and technologies such as water-supply-augmentation technologies (e.g., desalination and wastewater treatment plants) be mainstreamed rather than remaining a niche?
19. How do we embed natural capital thinking into the water industry so that green solutions are considered a legitimate alternative to the end of pipe gray solutions?
20. How can green/private investment be utilized more effectively to support sustainable water management?
21. How does poor water quality (and subsequent environmental impacts such as coral degradation) impact the well-being of local populations?

Climate-change-related questions

22. How do water and sanitation utilities and other service providers become climate resilient?
23. What is the impact of seawater intrusion on domestic water supply in coastal regions?

Water and sanitation safety and risk management

Thematic question: what are the pathways to improve water and sanitation safety and risk management in human populations?

Water pollution, fecal sludge, and wastewater management are among the foremost challenges facing societies across the world. The United Nations estimate that 80% of global fecal sludge and wastewater go untreated.[27] The questions selected through the survey and refined by expert opinion raised in this theme address the concerns proposed by the UN SDG 6.3, i.e., reducing risks to human health and the environment through reducing pollution and effectively treating and increasing the safe re-use of fecal sludge and wastewater. Questions under this theme confirmed the responses received by a similar scoping exercise in urban stream ecology,[28] indicating the need to strengthen research on improving safety and risk management in the interphase between hydrological systems and human settlements.

Existing research suggests that nutrients like nitrate in drinking-water sources are largely governed by fertilizer inputs from agriculture, wastewater discharges, and hydrobiological processes, which inevitably affects water quality and create conflicting interests between stakeholders.[29] The outcome of our scoping exercise identifies a range of questions that examine the societal impact of poor water quality and pollution and highlight the inequitable impacts of these on disadvantaged populations. Submitted survey questions draw attention to the efficacy of existing national policies and institutional frameworks in addressing the complex social inequalities that arise out of water pollution, i.e., by investigating who pays for what, losses and benefits from water pollution, critical polluting activities, and actions to improve drinking water quality. Expert interviewees drew attention to the fact that while the principle of "polluter pays" may be accepted in theory, there are questions of whether governments/regulators can hold powerful polluters accountable.

The technological challenge of addressing an ever-evolving diversity of pollutants in waste treatment processes also strongly resonates with this theme.[30] However, both submitted questions and expert interviewees direct attention to the point that addressing risk management is fundamentally about state capability as much (or more) than it is about new technologies. In doing so, they interrogate how advances in industrial and agro-industrial technological processes are accompanied by new pollutants that pose challenges and have knockon effects on the costs of water treatment[31,32] and how emerging point-source pollutants such as micro-plastics, bioactive pharmaceuticals, endocrine disruptors, persistent organic pollutants, and cosmetic products introduce significant additional costs. Additionally, the scoping exercise flags how the failure to keep human waste from polluting the environment is contributing to the development of anti-microbial resistance in many human pathogens.[33]

Questions 24–38 of the top 100 questions in this scoping exercise fall into this thematic area and broadly encompass issues of water safety and quality, a significant emphasis on the management of fecal sludge and wastewater, and how climate change will impact these dynamics in the future.

Water safety, quality, and delivery

24. How can water allocation for the environment be improved with respect to water quality?
25. What are the long-term chronic effects of water contamination by agro-toxins used in industrial agriculture?
26. What are the impacts of intercatchment water transfer in relation to water quality, chemical composition, invasive species, and the genetic integrity of aquatic population?
27. What is the pollution impact of international trade, and how can the pollution impact of this be addressed at the global level?
28. What is the extent and impact of transboundary water pollution, and who (really) bears that cost?
29. What laws, policies, information, and institutions are required to hold polluters accountable for environmental impact?

Sanitation safety and the management of fecal sludge and wastewater

30. How can responsible agencies manage different sources, pathways, removal, and recovery of pollutants (on land and in drinking water) to reduce aquatic pollution?
31. What laws, policies, information, and institutions are required to effectively prevent source pollution?
32. How can cost shifting and externalities in production processes resulting in water pollution or depletion be prevented or minimized?
33. What modifications to fecal sludge and wastewater treatment and re-use are needed to avoid pollution of ecosystems with emergent pollutants, such as micro-plastics and organic chemicals (e.g., hormones) arising from cosmetics and medicines?
34. What landscape-management arrangements can most effectively and sustainably reduce losses of nutrients, soil, and agrochemicals and the dispersal of gut pathogens from farmland to surface and groundwater while minimizing adverse effects on crop and livestock production efficiency?
35. How can the technologies in the fecal sludge and wastewater treatment process be advanced to remove an increasing diversity of pollutants?
36. How can the recovery of pollutants be affected by land management?
37. What are the opportunities for nutrient recovery from fecal sludge and wastewater?

Climate change

38. What will be the impact of climate change on water pollutants including pathogens, algae, and nutrients?

Water security and scarcity for human populations

Thematic question: how can the competing demands of different water users be reconciled?

Questions 39–53 below of the top 100 questions relate to the question of water security and scarcity. In particular, they focus on the necessity of understanding the consequences of increasing and competing water demands and how human societies can better respond to them at an appropriate governance level.[34] The submitted survey questions emphasize concerns with population growth, mass conflict, rising levels of affluence, global trade interconnectivity, climate change, and economic-induced migration toward large population centers.[35,36] Our expert-led review of this area highlights that, increasingly, water scarcity is being experienced in areas where water demand is subject to competing use interests such as bulk water transfer, power generation, and agriculture embedded in the form of trade in goods and services.[37]

The submitted questions raise a diversity of concerns as to how global human challenges such as migration, health, and conflict relate to water scarcity and security. Given the timing of our scoping exercise, expert analysis in this area saw the COVID-19 pandemic as exacerbating existing inequalities.[38,39] Hence, the final list of questions in this theme draws attention to debates that go beyond physical availability and encompass water use embedded in exported goods and services (water footprint); waterborne pollution associated with material production (water quality); lack of investment in infrastructure or insufficient human capacity to satisfy the demand of water (economic water scarcity); and how the allocation and access to water might be rebalanced (water security).

39. Could water (or the lack of it) spark the next major global conflict?
40. What are the main global impacts of water insecurity on health?
41. What will be the implications of global migration and climate warming on the impact of water- and vectorborne diseases?
42. What impact is rapid urbanization, population growth, and industrialization having on water security?
43. How are water scarcity and security influenced by degrading water quality?
44. What are the on- and off-site impacts of land degradation on water security?
45. Could water security be achieved by regulating the production of high-water-demanding crops/beverages?
46. Does water scarcity only become politically significant when elites are impacted?
47. Do the decreasing water availability scenarios present an opportunity for powerful private actors to capture the natural resources of developing countries in the name of water security?
48. What laws, policies, information, and institutions are required to enable sustainable water management in a dynamic context?
49. What incentives can be built into regulating sustainable groundwater use in agriculture?
50. How can water rights be balanced between industrial water users and farmers, considering the power dynamics between these two water users in different contexts?
51. How do water challenges shape migration dynamics?
52. To what extent can imports of virtual water through food imports be utilized to conserve water domestically and achieve water and food-security goals?
53. How can hotspots of competition for water between the environment and human demand be better identified?

Hydroclimate-ecosystem-Anthropocene dynamics

Thematic question: what are the dynamics and interrelationships between hydrology, ecosystems, and human-induced changes on land, water, and climate?

Questions 53–71 of the top 100 questions in this scoping exercise sit under this broad theme.

Submitted questions were concerned with understanding the fundamental dynamics of ecosystems so that human impacts can be accurately assessed. That is, how ecosystem processes are affected by land use and other drivers such as climate change,[40] how these changes affect people and society, and how society's responses feed back into biophysical functioning.[41,42] This theme contains questions that interrogate the dynamics between human societies, hydrology, ecosystems, and climate. They also highlight a topical focus on nature-based solutions (NBS)—i.e., actions that work with and enhance nature as essential in climate-change adaptation, urban water challenges, and sustainable water management[43] and the value of interdisciplinarity in research to elucidate hydroclimate ecosystem and Anthropocene dynamics.[44]

Expert-led interviews in this theme highlighted that integrated interdisciplinary approaches that couple ecological and socio-economic knowledge have now firmly entered the academic and environmental management agendas,[45] albeit much less so in terms of incorporating cultural aspects.[46] This integration has been attempted in various ways, often relying on the development of models to establish, quantify, and map the "services" delivered by ecosystems under different management scenarios, in combination with economic data elicited via various valuation methods.[47] While these approaches represent significant knowledge advancement, producing a set of model outputs that can be linked in one way or another to one or more ecosystem dynamics is not enough, and a number of the final questions ask about the limitations and applications of modeling. Additionally, they suggested that there can be a gap between the typical outputs of ecosystem models and the representation of such changes in terms that states and agencies can respond to and for which a social outcome (value) can be measured.[42,48] This discussion, therefore, influenced the selection of the specific research questions under this theme.

54. How can the costs of flood alleviation be weighed in relation to the economic cost of flooding?
55. How can landscapes be managed effectively to mitigate against drought and flood risk while at the same time enabling sustainable livelihoods?
56. How will the projected reductions in drying lakes and river-basin levels impact on biodiversity, socio-economic, and political stability in these regions and globally by the second half of the century?
57. To what extent can population pressure and land use, such as erosion/siltation, impact the hydrological cycle?
58. To what extent do current approaches to natural management lead to nature (water) commodification, and what are the risks associated with this?
59. Which tools need to be developed for the reduction of upstream degradation, in-stream activities resulting in sediment deposition in rivers, lakes, wetlands, and dams?
60. What are the possibilities of reducing the impacts of hydropower production on downstream ecosystems by revising the operation of dams?
61. How can hydropower be re-engineered as an efficient source of green energy to reduce its negative effects on aquatic ecosystems?
62. What is the effectiveness of payment for environmental services (PES) or climate finance as instruments to address or reduce negative human impacts on ecosystems?
63. What is the most cost-effective way to incorporate NBS into integrated land-use and water resources management?
64. What effect do sediment transport processes have on the efficacy of natural flood-management measures?
65. How can the impact of natural flood management be assessed alongside other flood-management solutions in common flood-modeling packages?
66. What research is needed for widescale implementation of blue and green infrastructure?
67. How can NBS be harnessed to resolve urban water challenges?
68. How do we embed natural capital thinking into the water industry so that green solutions are considered a legitimate alternative to the end of pipe gray solutions?
69. How can green/private investment be utilized more effectively to support sustainable water management?
70. What effects do natural flood-management measures have on fluvial sediment fluxes?
71. What are the systemic barriers to implementing measures that should meet multiple goals for water management—especially natural flood management/natural water retention measures/working with natural processes?
72. What is the best way to re-integrate the many benefits of natural processes into policy and technological decisions, countering an automatic presumption in favor of electromechanical engineering solutions?

Multi-level governance

Thematic question: what are the critical challenges for the governance of human interactions with water?

In identifying the top 100 questions for post-2015 development, Oldekop and colleagues identified governance as one of the key cross-cutting research agendas relevant to achieving development in the next decade.[49] Five years on, the question of governance remains a major priority research theme, as inferred from the survey data and expert interviews. Questions 72–85 of the top 100 questions in this exercise are clustered in this thematic area.

Fundamentally, these questions relate to how human societies at all levels "govern" water resources—i.e. the complex political, economic, and social processes that characterize water resource decision-making.[50] "Good" governance is prescribed in SDG 6.5.1 through the concept of integrated water resources management (IWRM). However, "good governance" and the application of IWRM have been the focus of intense debate.[51] The submitted questions and the insights of our expert panel draw attention to the concern that such prescriptions neglect the complex governance realities of specific contexts and that the challenge of achieving "polycentric" and adaptive water governance is limited by state capability.[11,52–54] Under this theme, survey questions engage with how institutions can be capacitated to deliver appropriate governance that goes far beyond the creation of policies that align themselves to dominant international jargon and agendas (e.g., IWRM). The questions under this theme fall into two spheres: the international and the local. The central thrust of the submitted questions here is one of how institutions and capacity evolve to respond to the collective challenge of sharing water resources at the local level and how the outcomes can be equitable and just.

International governance

73. How could global institutions like United Nations (UN)-Water be capacitated to actively work on finding solutions to the global water and climate crises?
74. What laws, policies, information, and institutions are required to enable effective transboundary international water diplomacy?
75. What role can and should external parties play in the transformation of water-diplomacy interventions?
76. What factors enable effective transboundary trust and relationship building?

Local water justice and institutions

77. What role do institutional and community politics play in community water access and distribution?
78. What is water justice, and how could it be achieved?
79. What are the necessary institutional changes required to move toward water-related social-ecological justice?
80. What is the place of spirituality, religion, and culture in the governance of water, and can these be valued in water management?
81. How can historical and cultural perspectives be integrated into decision-making on water resources?
82. How can the full values, including benefits as well as costs, of all interconnected ecosystem services be integrated into policy and practice decisions?
83. What laws, policies, information, and institutions are required to adjudicate differential stakeholder participation and demands for water resources?
84. How can central government water resource offices (ministries of water resources [WR], etc.) be strengthened to facilitate IWRM?
85. How can the political economy (of countries, districts, communities) be altered and incentives created to enable WR offices to have more control over WR outcomes in situations where water-consuming sectors like agriculture and energy are more powerful than the WR ministries?

Knowledge production

Thematic question: how can water and sanitation research from multiple disciplines collectively work with governance systems to inform policy and human actions?

The final 85–100 questions in this scoping exercise entail aspects of knowledge production and communication. Submitted questions to the survey demonstrated a concern for better integration across separate disciplines in water research. According to participants' questions and in the view of the expert informants, part of this challenge lies in addressing the limitations posed by research funding agencies that introduce often rigid disciplinary barriers and reinforce unequal relationships of power between institutions.[24] In addition, the set of questions around citizen science reiterated one of the key concerns of the water community as a possible mode of strengthening data measurement, observation, and communication.[55]

The submitted questions also draw attention to power imbalances in the production, consumption, and ownership of data and information. Our expert reviews pointed out that data never speaks for itself. It must be transformed, synthesized, and explained, and "science" cannot define policy or mandate action. Political decisions and funding allocation shape what research gets done, and the dynamics of power and finance shape how data are collected and used. The past shape of research on water (and most development issues) has at times and in some contexts been overtly colonial and racist.[56] As the questions suggest (e.g., Qs 89 and 90), there needs to be collective effort to actively address genuinely inclusive co-production in research.

Interdisciplinary challenges

86. Does a focus on global challenges and SDGs neglect the importance of a more local and contextual approach?
87. What is the role of interdisciplinary research in assessing and quantifying the multiple contributions of water to human well-being in all its dimensions?
88. How can researchers build synergy and co-production across disciplines?
89. How can the current modes of research funding be improved to be compatible with the needs of sustainable and long-term research that addresses complex socio-ecological challenges (e.g., longer project times, processes that are shaped as researchers go along and engage with stakeholders, longer-term funding, size of research groups, the scope of the funding opportunities, etc.)

Data science-technology challenges

90. What are the opportunities available to translate the huge amount of data and information provided through research into usable tools/products/solutions for the effective governance of water ecosystems/catchments?
91. What are the barriers to accessing climate and hydrological data for scientists and policymakers in some regions?
92. How can new technologies (machine learning, big data, precision farming, climate/weather forecast) support water management effectively?
93. How can Earth observations data be converted into practically useable information for operational water users?
94. How emerging technologies and qualitative methods be used to understand drivers of human water use decision-making?
95. How can citizen science be harnessed to monitor progress toward SDG 6 in data-poor regions?
96. What role could citizen science play in enabling community representatives to start performing water quality analysis on their own?
97. What is the best approach to combine insights from remote sensing and citizen science to improve river health monitoring?
98. How can researchers and governments employ emerging technologies such as artificial intelligence to aid in the observation, modeling, and decision-making concerning future water-security scenarios?
99. What are the capabilities of existing environmental models to integrate and interlink the dynamic relationships between energy, water, food security, agriculture, and climate change?

100. How can better real-time spatial data across river basins on soil wetness conditions enable improved prediction of downstream discharge in response to real-time rainfall or weather forecasts?

These listed 100 questions are not intended to be definitive and absolute; rather, they are illustrative of the most often identified themes and suggestions in this scoping exercise.

Conclusions

This paper outlines six thematic and 100 illustrative questions for future water research. These reflect the priorities of a global scoping exercise by individuals working within the loosely defined boundaries of the "water sector." This has all the limitations of any self-selecting survey and expert-led prioritization exercise. We, therefore, do not propose that these are a definitive set of questions. However, what they do is offer a purposively interdisciplinary and multi-scalar framework for thinking about the nature and space of research relating to water. Large-scale water-research projects are frequently multidisciplinary in scope. The six thematic research questions enable researchers to position themselves and to communicate this to each other. It is our experience that this can be a challenge. It is therefore an insight into the current nature and internal dynamics of the field of water research.

Significantly, the scoping exercise reveals demand for recognition of power and politics as barriers to water access, drivers of major water issues, and significant factors in the shaping and implementation of research agendas. We recognize that call is not confined to our study but affirms other recently published work.[15,16,30] This is also not confined to social scientists but is a call from across disciplines, sectors, and societies. The six thematic water questions also draw attention to demands to challenge the status quo in water research. Within them, we observed a call for funders (and their funding chain agencies) to recognize the complexity and need for long-term institutional capacity building and to step away from quests for universal solutions and for researchers (and their institutions) to build genuinely interdisciplinary (and transdisciplinary) knowledge that recognizes multiple world views and to engage with the messy and normative arena of politics and governance as it happens in reality.[15]

The scoping exercise also shows an interest in justice: justice for the marginalized human populations who suffer from the excess consumption and pollution of the rich, and justice for the local and planetary ecosystems despoiled through a failure of governance across all scales of human life. We suggest that our scoping exercise can be read as a call for water research to create inclusive interdisciplinary approaches that ensure knowledge integration and co-production to inform robust governance systems that respond to multi-dimensional challenges from the household to the planetary level.

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

Further information and requests for resources should be directed to and will be fulfilled by the lead contact, Anna Mdee (a.l.mdee@leeds.ac.uk)

Materials availability

Material generated in this study will be made available through the Research Data Leeds Repository https://archive.researchdata.leeds.ac.uk/ and can be accessed using DOI: https://doi.org/10.5518/1144.

Data and code availability

The data for the figures in the main text are available within the supplemental information. All survey responses (anonymous) are available at the Research Data Leeds Repository: https://doi.org/10.5518/1144 .Extra coding steps and guide for this study are available from the corresponding author upon request.

Data collection

The scoping exercise began with the question what are the top 100 global water-research questions for the next decade? We designed a multi-step process (Figure S1) for the collection, filtering, coding, and refinement of research questions sourced from the global water sector.

Stage 1 entailed the creation of an accessible survey to harvest free-text research questions from anyone with an interest in water research. Stage 2 of this process necessitated the cleaning, sorting, and processing of submitted questions using NVivo software to generate a long list of the most recurrent questions. Thematic sorting of the long list of questions fed into an expert-led review to select the top 100 questions.

Stage 1: Survey design and distribution

The survey asked participants to submit their 10 top water-research questions in free text and was available online from January 23, 2019, to December 31, 2019. Respondents to the survey identified themselves according to their geographical location and occupational affiliation. Active tracking of survey responses according to geographical spread took place, and efforts were taken to ensure the promotion of the survey to address gaps in geographical coverage. A Spanish language version was created to fill one of the larger geographical gaps. The survey was, however, not translated to other languages, reflecting the resource constraints of the team.[57]

In the survey-distribution stage, we conducted a systematic internet and networking search that produced a list of government agencies, research institutions, NGOs, and water agencies. Our search produced 355 international water agencies, state water ministerial offices, research and training centers, and water member organizations, such as the International Water Association (IWA), Global Water Partnership (GWP), Rural Water Supply Network (RWSN), and the World Water Council. Snowballing sampling from our collective networks in addition to the targeted search identified 999 individuals across all continents. The survey link was shared with these individuals through emails. In the corresponding emails, individuals and organizations were encouraged to share the survey with their contacts and networks. The survey was featured on the websites, social-media posts, and newsletters of these international networks. It was further distributed through water@leeds members and other associated centers and faculties through newsletters, emails, and on social media (through Facebook, Twitter, LinkedIn, and ResearchGate). A QR link enabled easy access to the online survey.

Active participation in major water events (e.g., World Water Week 2019 in Stockholm, Sweden, International Water Association Young Water Professionals Conference in Toronto, Canada, and the 2019 Africa Water Show, Johannesburg, South Africa) also availed the survey directly to participants and encouraged a face-to-face engagement and discussion with the survey team.

Unlike similar prioritization exercises, the questions suggested by participants were not restricted to any specific aspect of the water sector.[58] No criteria were set in terms of how submitted questions should be framed; the participants were simply asked to identify their view of the top global water-research questions. The order in which the questions were submitted was not considered as an indicator of priority to avoid analytical challenges.

NVivo 12 software enabled the research team to clean and sort the 1,766 submitted valid questions using keywords and recurrent themes. This created a long list of 231 questions. More details on this process are supplied in next section.

Stage 2: Iterative expert interviews and prioritization

Stage 2 deployed an expert-led process to assess and refine the 231 questions in the long list.

We invited all survey respondents to indicate their willingness to engage in stage 2 (group 1). 252 out of 459 respondents agreed to be contacted further.

The original plan included an in-person stakeholder collaborative exercise to decide on the prioritized list of questions, with the stakeholder list selected from the 252 respondents who agreed to engage further. A mock stakeholder exercise was conducted in February 2020 with post-graduate students and staff of the University (name withheld) to test the method. However, in March 2020, an in-person workshop was impossible due to impending COVID-19 restrictions across countries. The team, therefore, designed an iterative online approach to assist in identifying the prioritized list of research questions. We purposively selected 20% (50 participants) of the agreed sample based on geographical location (to ensure geographical spread), sector (academics, industry, etc.), and availability.[7,59] An e-mail was sent to enquire if people were available to be interviewed. 15 participants responded with a date and became group 2. This enquiry took place between March and April 2020. We believe that the low rate of response was particularly because of the emergence of the COVID-19 pandemic.

We emailed out the list of pre-analyzed themes to participants in group 2. Participants were asked to choose any theme(s) of interest. The themes were identified through sorting of the data using NVivo 12 and included water quality, water supply, water use, water and agriculture, sanitation and wastewater treatment, water governance, water scarcity and demand, water security, and global water challenges. 12 participants responded. Participants were again emailed a list of questions corresponding to their chosen theme. Participants were asked to select their top ten questions (again, in no order) and to add reasons that informed their selection.

Follow-up online interviews probed the motivations behind the selection of their priority questions. We compiled the list of all the selected questions accompanied by interview responses and created a first draft of prioritized research questions.

An internal project stakeholder group was formed, made up of academics and practitioners researching water across various geographies, sectors, and disciplines, to assist in the final sorting process (group 3). The purpose of this stage was to facilitate an in-depth triangulation of the data derived from the survey. Each member of group 3 was provided with thematic questions aligned with their expertise. Group 3 became the authors of this paper and come from backgrounds covering economics, civil engineering, hydrology, anthropology, law, and environmental science. Participants were also permitted to reframe, refine, and suggest new questions and emerging subthemes.[21] Each participant was provided with full details of previous responses from other participants (group 2). Participants in group 3 were also interviewed one on one to solicit their views and judgement on the questions submitted by participants in groups 1 and 2. Participants' suggestions were centered on the reframing of questions and the refinement of the themes derived in the early stage.[59] This process led to the identification of the big 6 questions as a way of synthesizing the content of the 100 final questions.

Data and analysis

In total, we received 2,648 entries of questions, of which 1,766 were valid. Invalid entries contained inputs such as "NIL," "N/A," random signs, vague phrases, and symbols.

Using NVivo 12 automatic coding feature, we detected emerging themes. NVivo suggested a total of 486 automated themes in the English version. Themes with the most references/related entries (more than 10 references) were selected as the initial guiding themes for the categorization of the survey data. The selected themes were then used to create nodes in the software. The same procedure was applied to the Spanish survey dataset.

We created a codebook with a list of keywords that could be used to collect references (related entries) about the various themes. NVivo Advanced Query permitted searching through the survey data to identify where these keywords (and their synonyms) may appear in the data. The query results were coded into various broader themes. A manual broad sweep was done through the list of questions to verify if anything relevant was unaccounted for in the query process. The initial thematic analysis resulted in 10 themes with a total of 231 entries, each containing between 13 and 21 questions. The themes included water quality, water supply, water use, water and agriculture, sanitation and wastewater treatment, water governance, water scarcity and demand, water security, and global water challenges. The thematic results were exported into Microsoft Word for further manual refining, screening, and sorting. Questions with similar ideas were merged as one or treated as a sub-question of another. Incomplete, polar questions and statements were eliminated.[12,59] This reduced the number per theme to between 10 and 15 questions.

Stage 2 analysis proceeded through an iterative process of expert-led sorting and refinement. Correspondence and interviews with both groups 2 and 3 (outlined above) produced a draft of 100 priority questions and refinement of the initial 10 themes. By the end of stage 2, the 10 themes were refined into six (6) overarching themes/questions. These big themes are illustrative of the questions categorized under them. In addition, at this stage, with the assistance of participants in group 3, vague questions among the 100 research questions were rewritten for clarity of language, focus, and target for action.

Ultimately, the project team presented the final list of questions, themes, and methodology internally to members of water@leeds at the University of Leeds for a group discussion and to gain feedback, especially on the framing of the six overarching themes and thematic questions. The team at this stage was recruited from different departments across and outside the university. The disciplines involved political science, anthropology, economics, hydrology, engineering, law, and geography.

By the end of the reiterative process, the big six themes/questions were framed to draw attention to the multiple and nested scales of water research (see Table 1) and to enable a synthesis of the top 100 priority research questions revealed in the scoping exercise. Interview and discussion data from all stages were transcribed and served as a guide in the overall presentation of the results. Our 459 respondents submitted 1,766 questions for inclusion in the top 100 global water-research questions. Analytical processes outlined in section 2 then produced a list of top 100 questions organized into six overarching themes (Table 1).

Limitations

The results of any scoping exercise are shaped by who participates and the frame of data collection and analytical process. As such, this scoping exercise, though reflecting the views of project participants, has some limitations.

The first is the challenge in capturing the views of every stakeholder in the water sector.[59] Water travels through multiple scales: to and from the atmosphere, bounded in ice sheets, and through basins, households, settlements, continents, intercontinents, and globally, both visibly and invisibly. This is seen in the multiple and intersectional disciplines and perspectives through which water is understood. Likewise, water shares a deeper association with several other sectors: energy, food, minerals, and climate change being a few examples.[60–62] While the team tried to ensure geographical, disciplinary, and sectoral coverage, it is important to acknowledge that the water sector is not a tightly bound and identifiable entity. Therefore, this scoping exercise reflects the views of the networks and organizations contacted, with a predominance of the academic sector.

In addition, in an exercise such as this, it is very difficult to correlate the positionalities of respondents with the kind of questions submitted. While it is the hope of the project team, in light of such global exercises, to ensure objectivity is a challenge. It is impossible to know whether questions suggested by individuals stemmed out of personal, country, institutional, or sectoral perspectives rather than an appreciation of global and shared water challenges. For instance, the team observed a limited number of questions around sanitation and hygiene but a greater percentage on hydrology and water treatment, and this should be taken as a reflection of the interests of the respondents rather than as a measure of objective priorities of the water sector.

Finally, the data-collection protocol was shaped by the COVID-19 pandemic. Similar priority exercises have employed in-person consultation workshops, which permit an in-depth deliberation of questions by stakeholders.[12,55,58,59] The team faced the challenge of working with conflicting timelines and schedules, especially during the first few months of the COVID restrictions. This is reflected in the reduction in the number of participants in the latter stages of the research. Nevertheless, while our approach departs from our original plan, it offers a contingency guide for similar future scoping exercises undertaken in such conditions.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.oneear.2022.04.009.

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AUTHOR CONTRIBUTIONS

The study was conceptualized by the directors of water@leeds, with key leadership from A.M., J.H., and G.L.-G. A.M, A.O.D., and G.L.-G. led the delivery of the research by preparing the survey instrument and collecting and analyzing the data. A.M. and A.O.D. contributed equally to the writing up and revision of the entire manuscript. They received specific contributions and feedback from G.L.-G., L.S., J.M.-O., A.D., B.E., J.H., P.O., and M.A.C.-V. With the exception of A.M., A.O.D., and G.L.-G., all co-authors were key expert interviewees in the study.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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Supplemental information

The top 100 global water questions: Results of a scoping exercise

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Supplementary information

The top 100 global water questions: results of a scoping exercise

Table S1 Geographical distribution of survey respondents

Country	Number of participants
Afghanistan	1
Algeria	1
American Samoa	1
Angola	2
Argentina	15
Australia	4
Austria	1
Barbados	1
Benin	1
Bolivia	6
Bosnia and Herzegovina	1
Brazil	2
British Virgin Islands	1
Cameroon	3
Canada	3
Cayman Islands	1
Central African Republic	1
Chile	10
China	2
Colombia	19
Congo, Democratic Republic of the	1
Costa Rica	3
Cuba	1
Dominica	3
Ecuador	4
Egypt	1
El Salvador	1
Ethiopia	2
Finland	1
France	5
Germany	6
Ghana	4
Greece	1
Guatemala	3
Honduras	1
Hungary	1
India	71
Indonesia	2

Iran, Islamic Republic of	3
Isla Norfolk	1
Italy	2
Kenya	4
Latvia	1
Libya	1
Lithuania	1
Malawi	2
Malaysia	1
Mexico	17
Morocco	1
Nepal	2
Netherlands	9
Nigeria	5
Norway	1
Pakistan	2
Palestinian Territory, Occupied	1
Peru	18
Philippines	1
Portugal	1
Senegal	1
Serbia	1
Sierra Leone	1
Slovenia	1
South Africa	13
Spain	31
Sri Lanka	2
Suriname *	1
Sweden	4
Switzerland	2
Tanzania	13
Togo	2
Trinidad and Tobago	1
Turkey	1
Uganda	3
United Kingdom	79
United States of America	11
Venezuela	6
Viet Nam	1
Zambia	2
Unknown	22
TOTAL	**459**

Table S2 Distribution of survey respondents by sector

Sector	Number
Research Funding Agency	1
Private Company (Waste Management)	3
Professional Institute/Association	13
Local Government	14
Private Company (Other)	17
Regional/Provincial Government Ministry/Agency	18
Private Company (Water Utility)	20
Private Company (Consultancy)	25
Central Government Ministry/Agency	35
Other	43
Non-governmental organisation (NGO)	64
Research and Education	203
Unknown	3
Grand Total	459

Figure S1 Stages of survey and question sorting

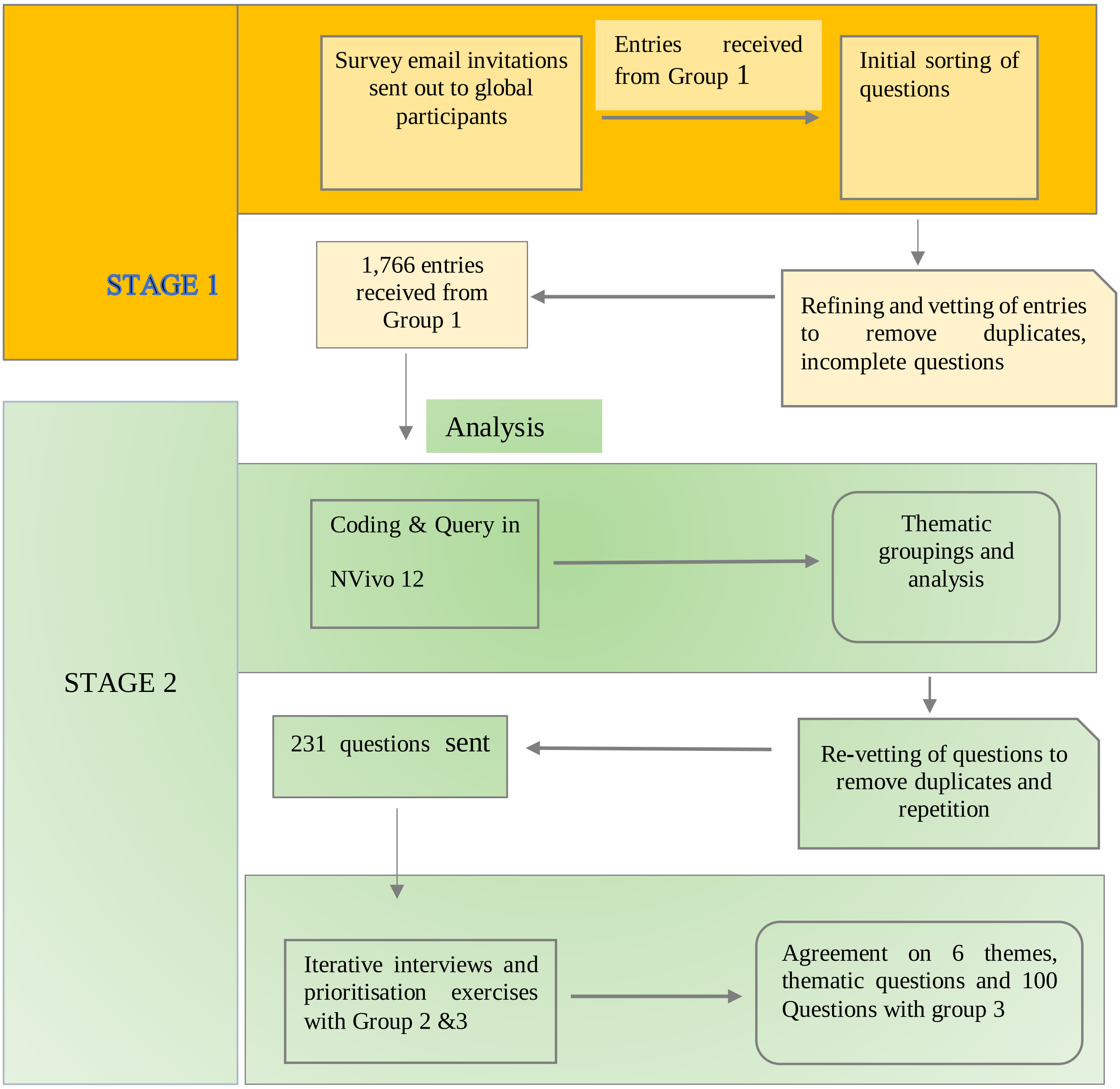
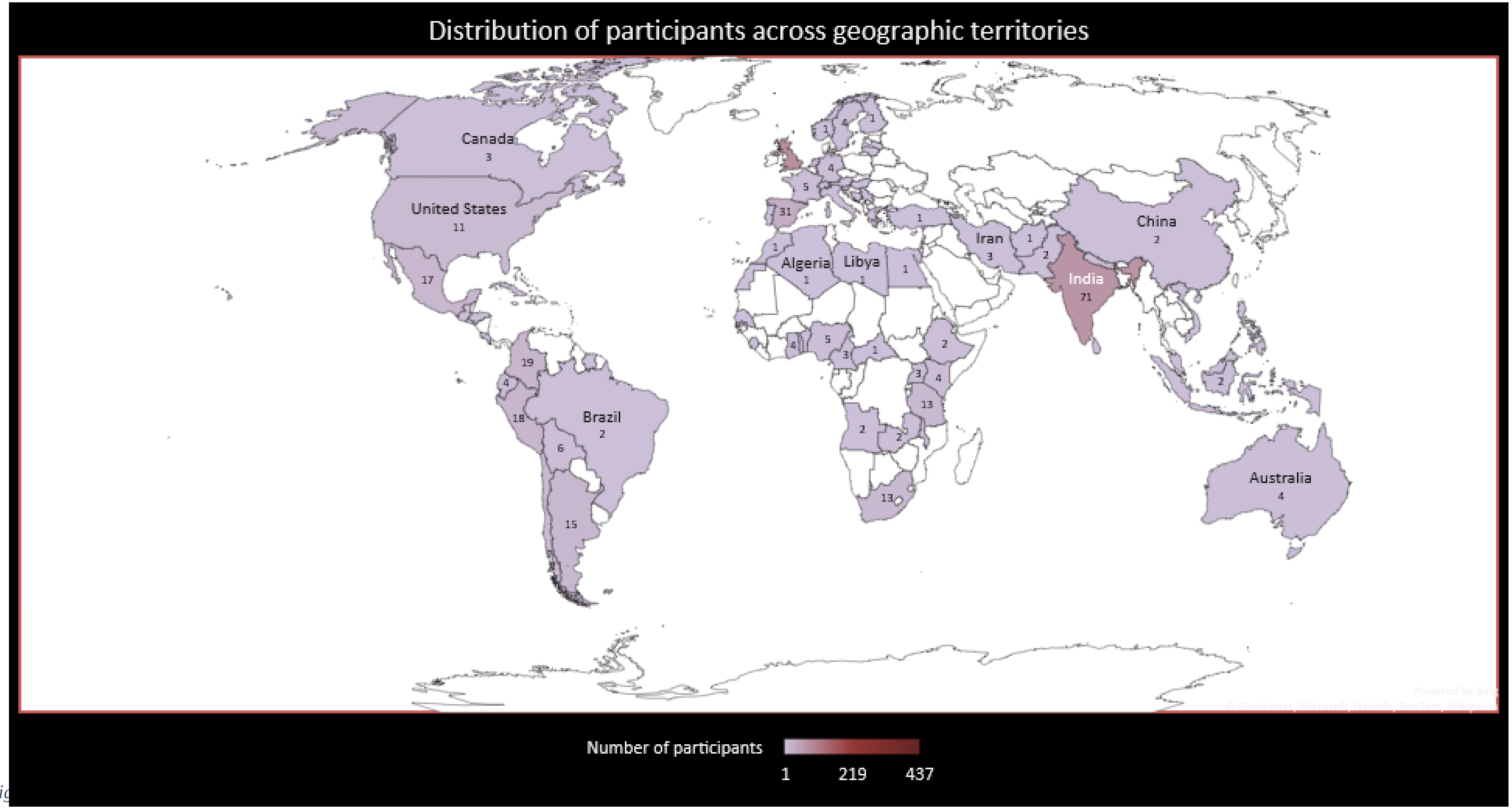


Figure S2 Distribution of survey respondents



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