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Conceptual framework of the MUISKA approach to assess multiple water-security risks

W.P. 3.2: Mapping hydro-climatic and pollution flows and risks

CAROLINA MONTOYA PACHONGO, BARBARA EVANS, MILLER CAMARGO VALERO
UNIVERSITY OF LEEDS
C.MontoyaPachongo@leeds.ac.uk

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1 INTRODUCTION

In this document, we displayed a proposed approach to assessing and comparing multiple water-security risks at basin level, moving beyond Integrated Water Resources Management (IWRM) to develop a tool for multi-dimensional water basin security planning. The underlying principle of this approach is to develop credible estimates of the relative risk burdens.

The term water security acquired popularity since the Ministerial Declaration of The Hague on Water Security in the 21st century. This was issued at the World Water Forum in 2000 (Ministers and Heads of Delegation, 2000) and has reached a prominent position among development actors and water professionals and within academia and governments (Lautze and Manthrithilake, 2012). Several definitions of water security exist, and we do not intend to discuss the correctness of all or some of them. However, we want to highlight two definitions of water security, which we believe are in line with the approach we are going to describe in this document:

1. "*Water security, at any level from the household to the global, means that every person has access to enough safe water at affordable cost to lead a clean, healthy and productive life, that the vulnerable are protected from the risks of water-related hazards while ensuring that the natural environment (freshwater, coastal and related ecosystems) is protected and political stability is promoted. Those using and sharing river basins and aquifers must manage their water sustainably, balancing water use for human development with protection of vital eco-systems and the ecological services they provide.*" (Global Water Partnership, 2000; Ministers and Heads of Delegation, 2000).
2. Water security is "*the capacity of a population to safeguard access to adequate quantities of water of acceptable quality for sustaining human and ecosystem health on a watershed basis, and to ensure efficient protection of life and property against water related hazards (floods, landslides, land subsidence, and droughts). Water security should be developed in a climate of peace and political stability.*" (Donoso et al., 2012; UN-Water, 2013).

Water security term also received some criticism because of policy documents and development discourse could include it as an abstract concept in but there was not a way to put it into practice (Lautze and Manthrithilake, 2012). In this line, Lautze and Manthrithilake (2012) suggest that quantification of water security may reduce ambiguity about the term and promote deliberation on the scales, thresholds, and degree of water security. Thus, indexes and indicators have been the most developed tools to quantify water security (Lautze and Manthrithilake, 2012; Babel et al., 2020;

Octavianti and Staddon, 2021). Emphasis on quantification has also been laid on risk components to calculate probabilities of hazards and vulnerabilities and then express their respective uncertainties. However, in the current proposal we recognise that, given the hydrocomplexity of the system we intend to study and data availability, we will not characterise all hazards, vulnerabilities and resulting risks in terms of probabilities and we will apply qualitative methods instead to characterise them together with the strength of knowledge for all risks (van Asselt, 2000; Aven, 2020), then keeping the entire universe of risks in a river basin. In Appendix A, we include a guide to judge the strength of the knowledge.

The international project Water Security and Sustainable Development Hub, funded by the Global Challenges Research Fund (GCRF) and United Kingdom Research and Innovation (UKRI), was conceived with the vision of enabling sustainable water security through developing and indicating a system approach that better understands water systems, values of all aspects of water, and strengthens water governance to enable integrated water management. This is being done through five work streams, as shown in Figure 1.

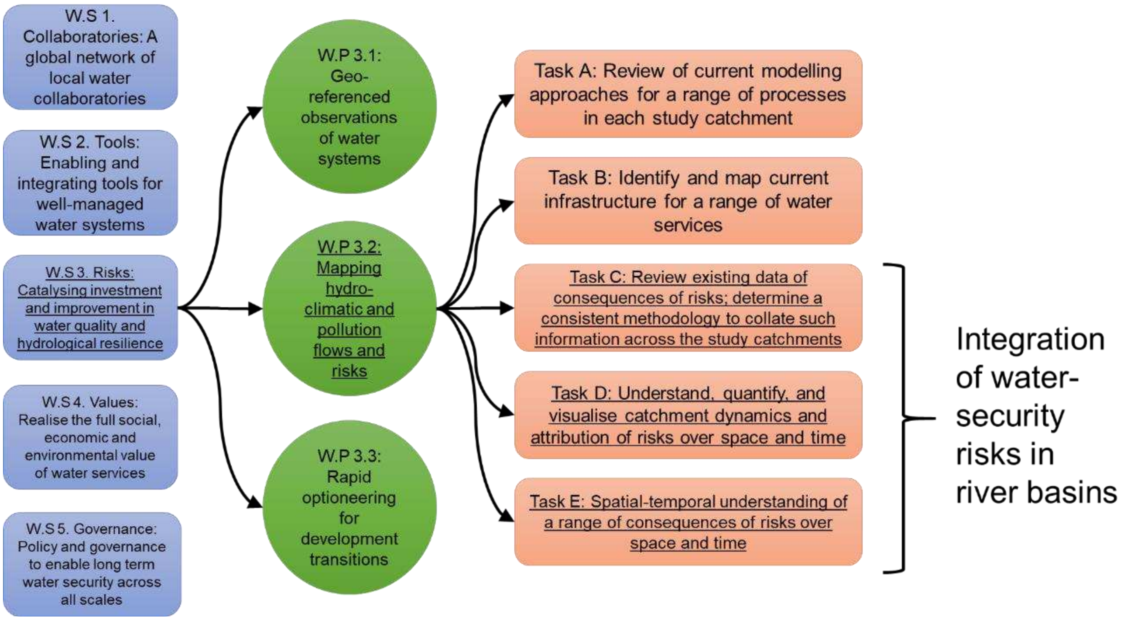


Figure 1. General structure of the research conducted by the GFRC Hub

The current proposed approach intends to contribute to tasks C, D, and E of W.P 3.2 (Figure 1) by assessing water-security risks based on risk science fundamentals. We call this approach MUISKA, which stands for **MUI**tidimensional r**ISK A**ssessment. We will apply MUISKA to one basin being studied by the GCRF Hub. To assess water-security risks, these can be characterised by the expected consequences of activities (probability of hazard occurrence, probability of exposure, and expected damage or vulnerability), uncertainties of such consequences and the judgement of the strengths of the knowledge (consequences and uncertainties) (Aven, 2020).

The following sections state the aim of this work and present the foundations and structure of the approach, and definitions and treatments of its fundamental aspects. We also describe how this study fits into the entire structure of the Work Stream 3 of the GCRF Hub. At the end of this document, we compare our proposed approach with IWRM (Global Water Partnership, 2018) to indicate how decision makers can use the former based on the latter. Finally, we include the Appendix A with a glossary of the definitions of key concepts we use throughout this document. The Appendix B specifies examples of risks originated by several hazardous events and expressed at different scales and dimensions.

2 AIM

To develop a conceptual framework for assessing and comparing multiple water-security risks at basin level, based on secondary data, at either population or non-population dimensions.

3 FOUNDATIONS OF THE MUISKA APPROACH

3.1 Key concepts

Water-security risks are complex and operate and impact at a range of scales and dimensions. Adding to the complexity, populations and physical assets may have multiple vulnerabilities. To explain the complexity of human and societal interactions with water systems, where a web on intricate dependencies across biotic and abiotic subsystems exists, Kumar (2015) introduced the concept hydrocomplexity. Hydrocomplexity is “*an integrated approach, aimed at taking a broad contextual view of water in all its complexity to seek out principles and methodologies to unravel the interactions across hydrosphere, biosphere, atmosphere, cryosphere, lithosphere, and anthroposphere*” (Kumar, 2015).

Aven (2020) defines risk as *“the mental concept that exists when considering an activity in the future and involve two main features: i) values at stake (consequences with respect to something that humans value) and ii) uncertainties (what will the consequences be?)*”. Moreover, risk assessment can be understood as a systematic process to comprehend the nature of risk, express and evaluate risk, with the available knowledge (Aven, 2020). Accordingly, risk assessment can be accepted as a prospective practice to expect consequences or impacts of a hazardous event or activity.

Similarly, van Asselt (2000) listed the following characteristics to offer an operational definition of risk:

a) Risk should be logically sound

b) Reflective of scientific expertise

c) Reflective of public values

d) Responsive to social concerns

e) Acceptable to experts, the public, and decision makers

Considering the item c in the operational definition of risk helps to link the work the GCRF Hub is doing by the W.S. 4 (see Figure 1). Moreover, presenting risks that are acceptable to experts and stakeholders also links the work being done in the W.S. 5 (see Figure 1).

One common key element to several water security definitions is risks. The report Water Security & the Global Water Agenda explicitly acknowledges the need to manage risks among the essential elements of water security and recognises that dimensions interacting with water create a complex system, whose management requires interdisciplinary collaboration across dimensions, communities, and political borders (UN-Water, 2013; Garrick and Hall, 2014).

In addition, water security and risk assessments can be seen as two sides of the same problem: more or major risks in a water system reduce its security and water security can help to manage risks [e.g., Lautze and Manthrithilake (2012) incorporated water security for risk management in an indicator as the dam storage capacity to counteract inter-annual rainfall variability in a country]. In the current approach, we understand risk assessment also as a tool contributing to achieve water security.

Because of the complex nature of water-security risks we intend to analyse in a river basin, i.e., hydrocomplexity, it is important to define systemic risks associated with complex systems. Thus, we use the definition offered by Renn and co-authors. A systemic risk must meet the following conditions: high complexity regarding causal or functional relationships (no linear cause-effect relationship but multiples negative and positive feedback loops instead), multiple uncertainties, being associated with cascading effects within the scale in which the risk is located and beyond this scale, and major ambiguities (Renn et al., 2020). Schweizer et al. (2021) also states that high dependency on contextual factors is one characteristic of systemic risks. Kumar (2015) also advocates for interdisciplinarity to develop approaches to study the emergent dependencies present when studying complex water systems.

Kumar (2015) also offered key characteristics of emergent risks (or black swans) associated particularly with water systems: i) causes and effects are separated in time and space; ii) interdisciplinarity is needed to develop effective approaches to hydrocomplexity; iii) there are high uncertainties about the proper solutions leading to desired outcomes; iv) new hazards or risks can be created when a new solution layer is built on top of existing layers, which creates novel dependencies in the water system; and v) it is difficult to find trade-offs for solution options due to complex societal values. For a practical definition of risk in the current approach, we adopt the concept of disaster risk (Box 2) to assess water-security risks in terms of hazards, exposed people or assets, and their vulnerability.

Kumar (2015) and Simpson et al. (2021) offer definitions of other types of risks, which are included in the supplementary material of their paper. Definitions of emergent, residual, compound, disaster, and cascading risks are in the following boxes.

Box 1. Emergent risks

A risk that arises from the interaction of phenomena in a complex system and that are generally not well integrated or included into current risk analysis. For example, the risk caused when geographic shifts in human population in response to climate change lead to increased vulnerability and exposure of populations in the receiving region (Intergovernmental Panel on Climate Change, 2014).

Emergent risks result from the confluence of unanticipated interactions from evolving interdependencies between complex systems, such as those embedded in the water cycle (Kumar, 2015).

Box 2. Disaster risks

The likelihood over a specified time period of severe alterations in the normal functioning of a community or a society because of hazardous physical events interacting with vulnerable social conditions, leading to widespread adverse human, material, economic, or environmental effects that require immediate emergency response to satisfy critical human needs and that may require external support for recovery (IPCC, 2012).

Box 3. Compound risks

Box 4. Residual risks

The risk that remains following adaptation and risk reduction efforts (IPCC, 2019).

Single extreme events or multiple coincident or sequential events that interact with exposed systems or dimensions (IPCC, 2019).

Box 5. Cascading risks

Cascading impacts from extreme weather/climate events occur when an extreme hazard generates a sequence of secondary events in natural and human systems that result in physical, natural, social, or economic disruption, whereby the resulting impact is significantly larger than the initial impact. Cascading impacts are complex and multidimensional and are associated more with the magnitude of vulnerability than with that of the hazard (IPCC, 2019).

To conclude this section, the MUISKA approach incorporates hydrocomplexity, systems thinking and adopts the definition of disaster risk to identify water-security risks in terms of hazards, exposed populations or assets, vulnerabilities, uncertainties, and judgements of strength of the knowledge. We intend that the application of this proposed approach in river basins generates outputs that respond to the characteristics of an operative risk definition.

3.2 General structure of MUISKA

We propose the conceptual framework MUISKA for assessing and comparing multiple water-security risks at basin level, which will allow analysing risks simply without losing the nuance of the interlinked dependencies. Data scarcity in developing countries and hydrocomplexity generate high uncertainties on risk estimations, which evidence the need for more research on methodologies to identify black swans or emergent risks in water systems. Thus, filling the data gap for assessing water-security risks can be expensive and time-consuming. Consequently, MUISKA can be considered a basic risk assessment that enables an interdisciplinary community to identify and agree on priority areas for actions, by examining scenarios and including resilience as part of the vulnerability analysis in conformity with the principles of risk science (Aven, 2020; Thekdi and Aven, 2021).

To do this, we are simplifying the risk analysis but pursuing to keep the universe of potential risks as wide as possible, looking across the whole basin, where community and society actions are workable, but we have excluded major transboundary issues since they usually lie outside of the people's scope who live within the basin. Figure 2 is a schematic representation of MUISKA. Scales and dimensions can be viewed as a matrix with complex interactions across each other (Figure 2a). Risk consequences can arise immediately, in the short, mid, or long term (Figure 2a and b). Therefore, the risk assessment must clarify the time frame set for when the hazards were observed, and the time considered evaluating the consequences of such hazardous events (Logan et al., 2021).

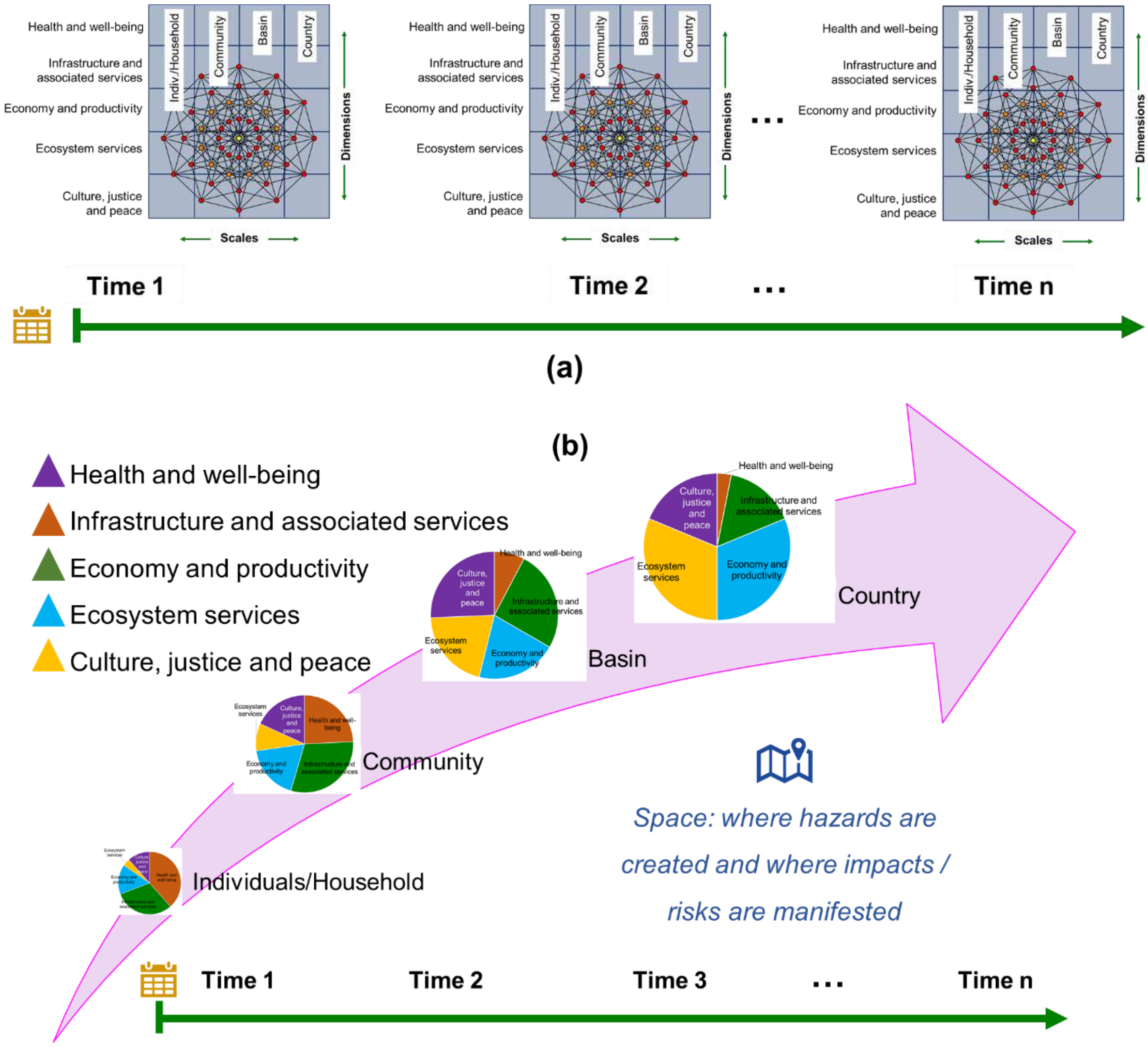


Figure 2. Schematic representation of the structure of MUISKA approach

In the MUISKA approach, we therefore set (Figure 2):

1. Four general scales of risk: country (C), basin (B), community (C), and individual/ household (H&I).
2. Five dimensions where impacts can occur: health and wellbeing (H&W), infrastructure and associated services (I&S), economy and productivity (E&P), ecosystem services (ES), and culture, justice, and peace (CJ&P).

3. Three categories of vulnerability: resilience, capacity, and condition (see Chapter 7).

Our general approach has six steps (Figure 3):

1. Define predominant hazards for the basin.
2. Describe qualitatively the consequences on the basin.
3. Involve GCRF Hub members and stakeholders in consulting priority consequences by discussing priority dimensions and scales of risk (different stakeholders may have different priorities) and identifying a shortlist of the most significant consequences on the river basin.
4. Undertake a risk assessment, tailored in depth and granularity to the scale of analysis and decision to be informed. In all cases, this will include the following generic steps.
    a) Including predominant hazards in the basin
    b) Carrying out an analysis of three types of vulnerability (capacity, condition, and resilience) in four scales and five dimensions
    c) Assessing how climate, socio-economic and other drivers of change will alter risks through time
    d) Defining uncertainties
    e) Establishing the strength of the knowledge
    f) Establishing temporal considerations for evaluation of hazards and consequences
5. Visualise risk.
6. Consult to stakeholders to outline a risk management plan.

For the steps 3 and 4, we suggest using a decision-making process -e.g., Analytical Hierarchical Process (AHP)- to compare, discuss, and agree to priorities according to their values and the power relationships among stakeholders. Similarly to MUISKA, Tonmoy et al. (2019) developed a process for climate change risk assessments based on three levels of complexity. Based on the work of Tonmoy et al. (2019), we describe in Table 1 the objectives, requirements of base knowledge and level of engagement, and the expected outcomes of each step of MUISKA.

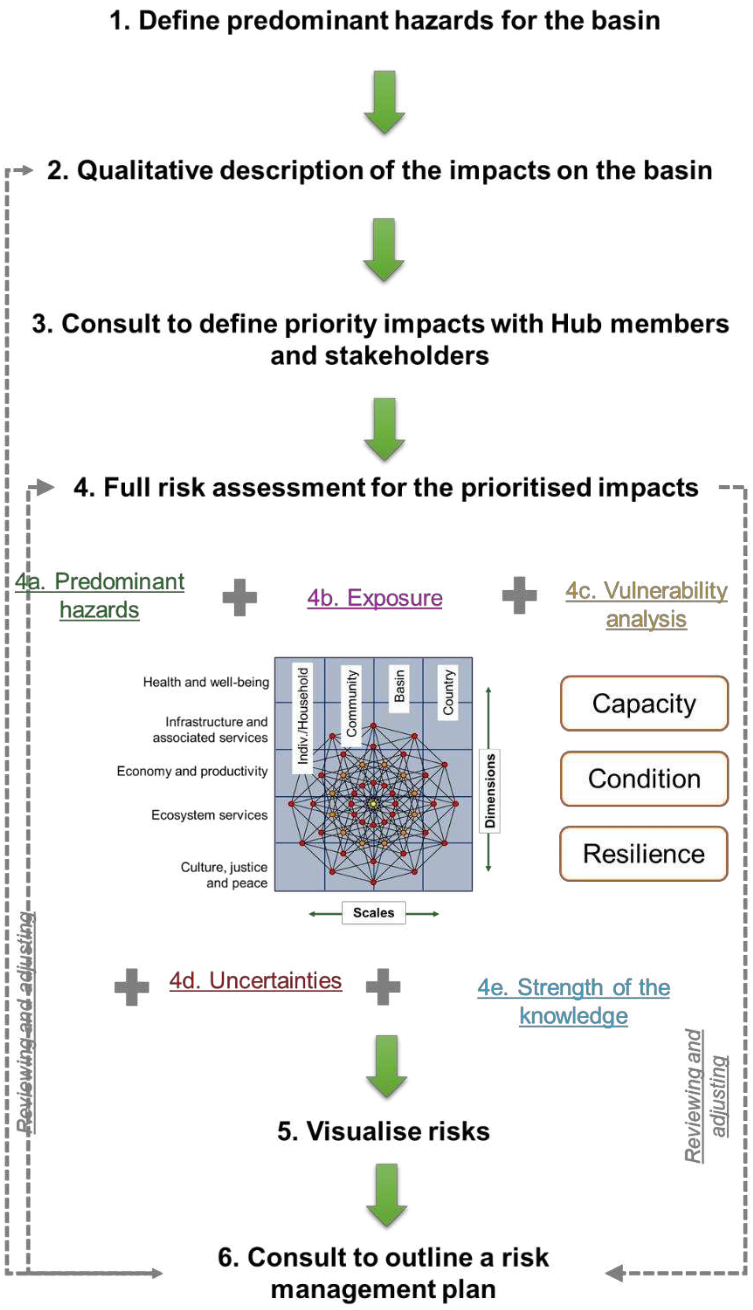


Figure 3. Schematic representation of the process proposed in MUISKA

Table 1. Characteristics and requirements of each step of MUISKA

MUISKA step	Objectives	Base knowledge requirement	Engagement requirement	Expected outcomes
1. Definition of predominant hazards for the basin	Develop a quick high-level understanding of the water-security hazards in the river basin	Local knowledge required to identify hazards and their history	Moderate expertise required to identify key groups of stakeholders and to interact with principal	Identified river basin stakeholders, level of interest and influencing

MUISKA step	Objectives	Base knowledge requirement	Engagement requirement	Expected outcomes
			members of those groups	Identified water uses and values associated with them List of predominant hazards in the river basin, categorised according to water quantity or quality, and characterised by the location where hazards are originated
2. Qualitative description of the impacts of hazards on the basin	Create a network of hazards and their consequences and identification of how basin subsystems are interrelated Identify interdisciplinarity cooperation needs, and promote systems thinking	Local knowledge required to construct the network of hazards and their consequences	Moderate expertise required to guide participants to build the network, incorporating systems perspective Moderate expertise required to understand the consequences of water-security hazards Moderate expertise required to interpret the results	List of problems/conflicts created from water uses Network of hazards and their consequences and identification of how they are interrelated (feedback loops) (see Appendix C) Classification of impacts according to scales and dimension
3. Consultation to define priority impacts	Define priority impacts of hazards by dimensions and scales Recognise values associated with prioritisation of impacts Recognise power relationships influencing the prioritisation	Active involvement of stakeholders is required to consult the priority impacts in the river basin	High expertise required to use tools for prioritisation of impacts Moderate expertise required to interpret the results	List of prioritised impacts by each stakeholder group, together with water values and power influences Identified ambiguities, divergences in judgements or disagreements among stakeholders
4. Full risk assessment	Assess the risks either quantitatively, qualitatively, or	Local knowledge required to define vulnerabilities	High expertise required to process data and interpret results	Description of time and space considerations

MUISKA step	Objectives	Base knowledge requirement	Engagement requirement	Expected outcomes
	mixed of the prioritised impacts Identify opportunities to create a general risk indicator or alternative ways to visualise / communicate risks by dimensions and scales	High expertise required to acquire specific data (may not be necessary for all impacts)	Moderate expertise required for communication or stakeholder consultation	included in the assessment List of risks by dimensions and scales classified by categories or described in detail Acknowledgement and description of uncertainties and strength of the knowledge
5. Visualisation of risks	Communicate the results of the risk assessment to stakeholders, academics, and general audiences	Local knowledge required to get stakeholder feedback on data visualisation	High expertise required to create data visualisation High expertise required for communication	Matrices, maps, spider charts, lollipop graphs, Sanky diagrams, infographics, etc.
6. Outline of a risk management plan	Provide a general guideline for risk management, including determination of research gaps associated with uncertain risks Recognise values and power relationships influencing the preferred actions and interventions Identify ambiguities within groups of stakeholders in relation to prioritised impacts and preferred actions and interventions	Active involvement of stakeholders is required to consult actions and interventions	Moderate expertise required for communication or stakeholder consultation	Concerted guidelines for water-security risk management for the river basin Identified relationships among water values, level of influence or power, and prioritised actions for risk management Determination of the consequences of risk management actions in relation to the creation of new risks or hazards or exacerbation of the existing ones Identified ambiguities, divergences in judgements or disagreements among stakeholders

Because of the dynamic and complex characteristics of water systems, hazard, exposure, and consequences should also consider differences among the place where the hazard is being originated, where the exposed scale is located, and where the risks or consequences are finally manifesting. Consequences can also appear immediately, such as destruction of bridges from a flash flood or in the long-term, such as posttraumatic disorders in people affected by such flash floods. In relation to time and uncertainties involved in risk assessments, we do not know yet if the immediate and long-term risks associated with flash floods are comparable or not to those linked to prolonged and continuously exposed ecosystems to antimicrobial substances.

Intensity, duration, and frequency should also be included in risk analysis associated with extreme weather events. For example, two low or medium-intense flood events happening in a short period (e.g., one year) in the same area might produce consequences with the same level of severity than one high-intensity event happening in the long term (e.g., 50 years).

In summary, MUISKA can be understood as a first-order risk assessment to be applied at a basin scale, but it would be necessary identifying smaller scale risks to prioritise areas for action. In addition, involving members of the interdisciplinary team of the GFRC Hub and stakeholders is desirable to increase the strength of the risk knowledge to produce a valid risk assessment in the water system (Aven, 2020).

4 SCALES AND DIMENSIONS

We propose to characterise risks according to four scales and five dimensions. Water-security risks can materialise at different scales, i.e., at individual or country levels. The scale of a risk points to the extent to which people, ecosystems, or assets receive it and their potential mitigation, compared to those which are received at basin level or across society. In the latter case, individual or community actions are unlikely to mitigate the effects, and responses need to be organised by the state or at basin level (usually as infrastructure or economic adjustments to water management practices or economic activities such as irrigation). At the level of individuals/households, we might also consider impacts that spread around the community (for example, outbreaks of water-borne diseases) and their control lies outside the individuals/households.

We established the previous considering that the concept of water security operates at all levels, from individual, household and community, to local, sub-national, national, regional and international settings (UN-Water, 2013). In addition, the Ministerial Declaration of The Hague on Water Security in the 21st century recognises that water security connects ecosystem protection, promotion of sustainable development and political stability, access to enough and affordable water services, and protection of vulnerable from the risks associated with water (Ministers and Heads of Delegation, 2000). Similarly, risks, once have been originated, may cascade from an individual or household level to societal level (Kumar, 2015; Renn et al., 2020; Simpson et al., 2021).

Our hypothesis, represented in the Figure 4, is that a small scale such as individuals/ households will feel the risk impacts mainly in the dimensions health and wellbeing and infrastructure; mildly in the dimension economy and productivity; and negligibly in the dimensions culture, justice, and peace and ecosystem services. As the scale size changes, the distribution of the impacts also changes. Thus, the scale basin may receive the risk consequences mainly in the dimension infrastructure, followed by health and wellbeing, economy and productivity, culture, justice, and peace, and ecosystems. In contrast, risk consequences in the dimensions infrastructure and associated services and culture, justice, and peace could be more relevant in the scale basin, followed by economy and productivity and ecosystem services and negligibly for health and wellbeing. Similarly, impacts on economy and productivity and ecosystems might be more severe on societal scale, followed by the dimensions culture, justice, and peace, infrastructure and associated services and health and wellbeing.

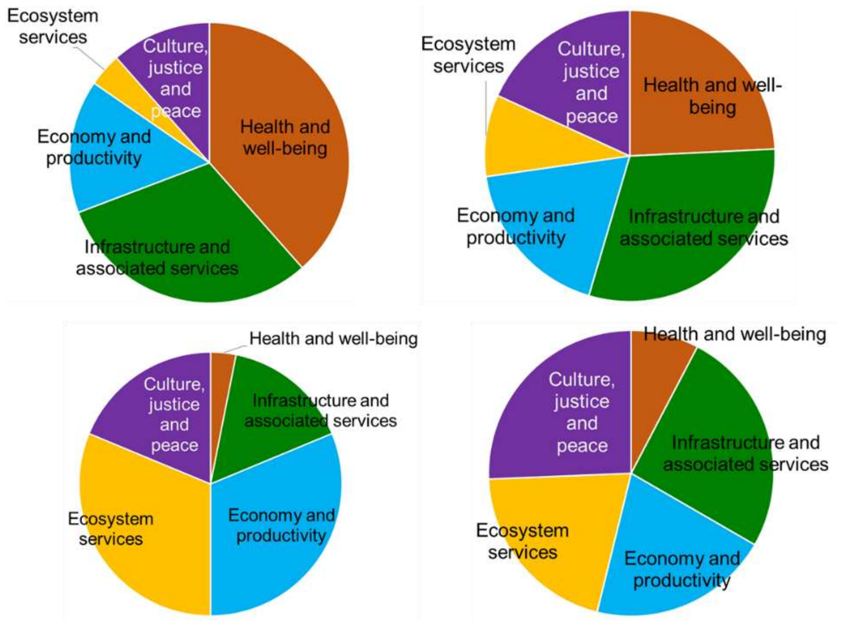


Figure 4. Hypothetical distribution of the weight of risk impacts on each dimension per each scale

Considering that methods and tools may differ for risk assessment in each scale, it is necessary to also define each of the scales proposed here for risk assessment in a river basin:

1. Individual: both physical character and inner reality, the existence of a world within each being. A human individual is characterised by being unique (Tuan, 2002).
2. Community: is a group of different individuals, living in the same geographic area (neighbourhood, village, or town), usually evoking something small, whose interaction is driven by cooperation to help each other and, therefore, by communication (Tuan, 2002). In all communities, practices used to maintain cohesion and identity are similar and are part of the need to confront nature and cope with human competitors and enemies (Tuan, 2002). In communities, personal relationships can be close and warm (Tuan, 2002).
3. Society: is also a group of individuals, often strangers to one another, larger compared to communities, and they either do not communicate or do so with less success, and their interactions are more complex (Tuan, 2002). Despite that society boosts individualism, personal relationships can be cold and superficial (Tuan, 2002).
4. River basin: a delimited physical area where all precipitations are caught and transported to the main river, either by run-off or by infiltration. In addition, in a river basin, the social, natural, and economic systems interact permanently and dynamically with water (Dourojeanni et al., 2002).

According to the systemic approach applied to risk assessments in water security, it is important to also define the concept of ethnic communities as they represent the link between environment and culture. Indigenous, ethnic, tribal, and traditional communities have predominantly land-based ways of life and have strong cultural and spiritual bonds to their traditional lands and resources. The way of life of ethnic communities is determined by their ecosystem (Bavikatte and Bennett, 2015). This is important when hazard-exposed populations are characterised in the MUISKA approach to identify the interconnections between ethnic communities and ecosystems and water values associated with them for further risk prioritisation.

Such risks expressed in one or more scales can also be classified by dimensions. We built MUISKA to consider dimensions such as health and wellbeing, infrastructure and associated services, economy and productivity, ecosystem services, and culture, justice, and peace. These were established considering that various factors, from biophysical to infrastructural, institutional, political, social, and financial elements are involved in water security (Donoso et al., 2012; UN-Water, 2013). Some approaches focus on the aquatic system (or the hydrologic/hydraulic system) to address the biophysical impacts, and some (notably IWRM – see Chapter 11) often take a more econometric approach (so focus on financial, social, political factors), but consideration for the actual assets themselves - the infrastructure - is still missing, particularly for the conceptualisation of water security that incorporates infrastructure (Octavianti and Charles, 2019). In line with this, our proposal covers this specific dimension because risk manifestation in the infrastructure can cascade into other dimensions at several scales, in the short, mid, or long term. Recently, the IPCC in its 6th Assessment Report for Climate Change (Intergovernmental Panel on Climate Change, 2021) included for the first time recent knowledge across dimensions and systems such as energy, urban and other settlements, transport, buildings, industry, and agriculture, forestry and other land use and cross-dimensional perspectives.

Table 2 shows the matrix of risk domains (dimensions and scales), which also has a column to specify the hazardous events that can lead to risks, according to vulnerability and exposure as well. Appendix A provides some examples of hazardous events and their consequences for each intersection. One example of what is meant by a risk in the dimension health and wellbeing associated with a hazardous event such as contamination of water for human consumption with pathogenic microorganisms is the occurrence of cases of acute diarrhoeal disease in children or adults, leading to increased number of disease cases in the community, more stressed medical institutions to attend new cases in the river basin, and the increased demand for physicians outside the river basin if the basin capacity is not enough to cover the sudden demand (vulnerability).

Table 2. Matrix of risk domains considered in the current conceptual framework with examples

Dimension	**Hazardous event**	**Scale**			
		Country (C)	Basin (B)	Community (Com)	Household / Individuals (H&I)
Health and wellbeing (H&W)	Hazardous event 1	Risk H-S1$_1$	Risk H-B1$_1$	Risk H-C1$_1$	Risk H-H&I1$_1$
		Risk H-S1$_2$	Risk H-B1$_2$	Risk H-C1$_2$	Risk H-H&I1$_2$
		Risk H-S1$_n$	Risk H-B1$_n$	Risk H-C1$_n$	Risk H-H&I1$_n$
	Hazardous event 2	Risk H-S2$_1$	Risk H-B2$_1$	Risk H-C2$_1$	Risk H-H&I2$_1$
		Risk H-S2$_2$	Risk H-B2$_2$	Risk H-C2$_2$	Risk H-H&I2$_2$
		Risk H-S2$_n$	Risk H-B2$_n$	Risk H-C2$_n$	Risk H-H&I2$_n$
	Hazardous event m	Risk H-Sm$_n$	Risk H-Bm$_n$	Risk H-Cm$_n$	Risk H-H&Im$_n$
Infrastructure and	Hazardous event 1	Risk I-S1$_1$	Risk I-B1$_1$	Risk I-C1$_1$	Risk I-H&I1$_1$
		Risk I-S1$_2$	Risk I-B1$_2$	Risk I-C1$_2$	Risk I-H&I1$_2$

Dimension	**Hazardous event**	**Scale**			
		Country (C)	Basin (B)	Community (Com)	Household / Individuals (H&I)
associated services (I&S)		Risk I-S1_n	Risk I-B1_n	Risk I-C1_n	Risk I-H&I1_n
	Hazardous event 2	Risk I-S2_1	Risk I-B2_1	Risk I-C2_1	Risk I-H&I2_1
		Risk I-S2_2	Risk I-B2_2	Risk I-C2_2	Risk I-H&I2_2
		Risk I-S2_n	Risk I-B2_n	Risk I-C2_n	Risk I-H&I2_n
	Hazardous event m	Risk I-Sm_n	Risk I-Bm_n	Risk I-Cm_n	Risk I-H&Im_n
Economy and productivity (E&P)	Hazardous event 1	Risk E&P-S1_1	Risk E&P-B1_1	Risk E&P-C1_1	Risk E&P-H&I1_1
		Risk E&P-S1_2	Risk E&P-B1_2	Risk E&P-C1_2	Risk E&P-H&I1_2
		Risk E&P-S1_n	Risk E&P-B1_n	Risk E&P-C1_n	Risk E&P-H&I1_n
	Hazardous event 2	Risk E&P-S2_1	Risk E&P-B2_1	Risk E&P-C2_1	Risk E&P-H&I2_1
		Risk E&P-S2_2	Risk E&P-B2_2	Risk E&P-C2_2	Risk E&P-H&I2_2
		Risk E&P-S2_n	Risk E&P-B2_n	Risk E&P-C2_n	Risk E&P-H&I2_n
	Hazardous event m	Risk E&P-Sm_n	Risk E&P-Bm_n	Risk E&P-Cm_n	Risk E&P-H&Im_n
Ecosystem services (ES)	Hazardous event 1	Risk E&S-S1_1	Risk E&S-B1_1	Risk E&S-C1_1	Risk E&S-H&I1_1
		Risk E&S-S1_2	Risk E&S-B1_2	Risk E&S-C1_2	Risk E&S-H&I1_2
		Risk E&S-S1_n	Risk E&S-B1_n	Risk E&S-C1_n	Risk E&S-H&I1_n
	Hazardous event 2	Risk E&S-S2_1	Risk E&S-B2_1	Risk E&S-C2_1	Risk E&S-H&I2_1
		Risk E&S-S2_2	Risk E&S-B2_2	Risk E&S-C2_2	Risk E&S-H&I2_2
		Risk E&S-S2_n	Risk E&S-B2_n	Risk E&S-C2_n	Risk E&S-H&I2_n
	Hazardous event m	Risk E&S-Sm_n	Risk E&S-Bm_n	Risk E&S-Cm_n	Risk E&S-H&Im_n
Culture, justice, and peace (CJ&P)	Hazardous event 1	Risk CJ&P-S1_1	Risk CJ&P-B1_1	Risk CJ&P-C1_1	Risk CJ&P-H&I1_1
		Risk CJ&P-S1_2	Risk CJ&P-B1_2	Risk CJ&P-C1_2	Risk CJ&P-H&I1_2
		Risk CJ&P-S1_n	Risk CJ&P-B1_n	Risk CJ&P-C1_n	Risk CJ&P-H&I1_n
	Hazardous event 2	Risk CJ&P-S2_1	Risk CJ&P-B2_1	Risk CJ&P-C2_1	Risk CJ&P-H&I2_1
		Risk CJ&P-S2_2	Risk CJ&P-B2_2	Risk CJ&P-C2_2	Risk CJ&P-H&I2_2
		Risk CJ&P-S2_n	Risk CJ&P-B2_n	Risk CJ&P-C2_n	Risk CJ&P-H&I2_n
	Hazardous event m	Risk CJ&P-Sm_n	Risk CJ&P-Bm_n	Risk CJ&P-Cm_n	Risk CJ&P-H&Im_n

The same hazardous event mentioned previously can represent risks to infrastructure associated with water supply: domestic installations (household/individuals); water treatment plants, distribution networks, and tanks (community and basin); and increased demand for pipelines, fittings, and chemicals for cleaning and corrective maintenance of affected water supply systems (country).

Similarly, the hazardous event "Flood" also affects human health and wellbeing of individuals, but in a more diverse way (physical and mental). At the community level, flood increases the incidence of disability and physical and mental diseases. In the river basin, flood can cause stress of medical institutions and more demand of rescue services staff. If such needs cannot be met with local or regional resources, national institutions must meet them or request international support. Flood consequences are also clear on infrastructure and associated services dimension because of the immediate impact on the functionality of houses; buildings; bridges; roads; and water, sanitation, electricity, and telecommunication systems. Flood may also impact the culture, justice, and peace dimension by loss of trust in institutions responsible for prevention and management of disasters (country); the isolation of communities, towns, villages, and municipalities (basin); separation of communities (community); and dissolution of families (household/individuals).

5 HAZARDS

Hazards considered in MUISKA include water quantity and water quality. In the MUISKA approach, we propose analysing hazards using three main divisions, such as floods, droughts, and poor water quality. Complexity and systemic characteristics of risks can be associated with complex and systemic hazards. We propose these three broad divisions to add just enough complexity to risk assessment, i.e., to untangle the complex relationships between risk factors to find a balance that allows us to compare risks among dimensions and scales. For example, a single hazard like a flood can immediately impact population and infrastructure, which can then cascade into the economy and productivity dimension. The same single hazard can also produce long-term consequences for human health and wellbeing, such as mental illnesses and disabilities. In relation to water quality and according to the scales described in Chapter 4, a hazardous event related to consumption of contaminated water with pathogens can cause diarrhoea cases in individuals and lead to an outbreak into community scale.

Similarly, a deforested river basin and a heavy rain event together may increase the content of suspended solids in a water source, making raw water impossible to be treated by plants located downstream because of turbidity surpasses their technological threshold, which leads to reduce or cease water supply. Another example of extreme risk is having a prolonged drought in a river basin and high environmental temperatures, leading to a low amount of water in the basin. This, added to discharges of industrial wastewater, increase the concentrations or organic matter and nutrients, which may increment the concentrations of disinfection by-products in drinking water if the water treatment plant cannot reduce organic matter content to safe levels before final disinfection with chlorine.

Here, it is important to highlight that drought is a phenomenon difficult to define and monitor because of its lethargic development and the multiple impacts created on several scales. In Appendix A, we offer four definitions of drought. In the example above, we refer to hydrological drought because of meteorological drought (National Integrated Drought Information System, n.d.).

6 EXPOSURE

Exposure can be defined as people, infrastructure, housing, production capacities, and other tangible human assets being subject to risk sources or hazards (Open Risk Manual Contributors, 2021). Such elements are the receptors of consequences, and their characterisation must include their location in relation to hazard production, gender, race, age, and socioeconomic status. For the characterisation of exposed communities, it is important to consider the ethnic groups in the river basin and the water values they must understand the relationships between communities and ecosystems and how risk communication and prioritisation must be addressed.

7 VULNERABILITY

Vulnerability in MUISKA means the inner property of the scale (individual/household, community, basin, country) exposed to a hazard related to a weakness, attribute, cause, or lack of control, which would allow hazards to cause harms (Función Pública, 2018). The analysis of vulnerability considers three types of vulnerability: resilience, capacity, and condition. We introduce them to incorporate the acquired capacity during lifetime from external sources to cope with stressors (capacity), the capacity of a system to cope with a disturbance, because of an inherent capacity and ability to return to a desired functionality (resilience), and the capability to hold both abilities during lifetime by proper maintenance (condition). This is favourable to identify and intervene in specific factors of vulnerability during risk management actions.

In environmental terms, the capacity of social, economic and ecosystems to cope with a hazardous event or trend or disturbance, responding or reorganising in ways that maintain their essential function, identity, and structure as well as biodiversity in case of ecosystems while also maintaining the capacity for adaptation, learning and transformation. Resilience is a positive attribute when it maintains such a capacity for adaptation, learning, and/or transformation (IPCC - Intergovernmental Panel on Climate Change, 2022). It is important to consider that such essential function, identity, and structure is system and context specific. Also, if the capacity for adaptation, learning and transformation was not enough before the hazardous event, then it will be weakened even more after this and the system will need more support for effective adaptation, learning and transformation to a desired functionality (Logan et al., 2022).

Despite of resilience is being developed as an independent science from risk science, resilience or lack of resilience can also be included as part of risk analysis by incorporating the recovery time given the occurrence of certain hazardous event and its associated uncertainties (Aven, 2020; Thekdi and Aven, 2021). Alternatively, such recovery time can be incorporated within vulnerability, despite of some authors prefer to restrict the vulnerability concept to situations where occurrence probabilities can be expressed, but including known and unknown hazardous events in the expression to characterise risks is also workable (Aven, 2020). Because of the complexity of water systems, some risk triggers are unknown, unpredictable, or complicated to expect; therefore, Renn et al. (2020) advise to focus more on resilience rather on the identification and prevention of risk causes.

With human beings, capacity can be understood in the proposed methodology as the ability to cope with continuous, frequent, or unusual hazards due to acquired resources through lifetime (reference). A known example of capacity is a complete vaccine programme, which helps to reduce vulnerability to infectious diseases in children and adults. For elements different from human beings, capacity refers to the amount of material components that such element can hold. For example, the maximum amount of water that can flow through a bridge without dragging it. The maximum pressure a wall can resist and remain standing during a flood event is another example.

Condition is directly related to maintenance of each element executed from someone external to that element periodically. For example, bridges must be inspected regularly to identify the first signals of structure erosion and prevent further failing. The availability of an appropriate number of medical doctors to attend population's needs shows people can get opportune health services and keep good physical and mental conditions. Table 3, Table 4, and Table 5 present examples of vulnerabilities for resilience, capacity, and condition, respectively, in each dimension and scale proposed here in relation to the three main divisions of hazards (floods, droughts, and poor water quality).

Table 3. Examples of capacity for each dimension and scale

	Scales			
Dimensions	Country	Basin	Community	Household / Individuals
Health and wellbeing	Strong institutions	Education	Education	Education

	Scales			
Dimensions	Country	Basin	Community	Household / Individuals
	Territorial planning considering water systems	Economic resources	Economic resources	Economic resources
	Strength of the system of sciences, research, and innovation	Vaccines	Vaccines	Vaccines
	Sustained growth in human and agricultural use of antibiotics	Strong health institutions	Territorial planning considering water systems	Awareness of environmental health risks
		Territorial planning considering water systems	Access to early warning systems	Limited sources of food
			Awareness of environmental health risks	
			Limited sources of food	
	Territorial planning	Existence of informal settlements	Established in informal settlements	Number of people per house
Infrastructure and associated services	Strong institutions	Strong institutions	Size of bridges and buildings	Number of floors in houses
			Age of buildings	Age of houses
Economy and productivity	Banking Regulation Insurance	Production capacity of goods	Production capacity of goods	Education
	Capacity to develop new technologies	Capacity to offer of services	Capacity to offer of services	Access to technology
		Access to technology	Access to technology	
Ecosystem services	Amount of biomass produced in an ecosystem CO_2 exchange	Amount of biomass produced in an ecosystem CO_2 exchange	Amount of biomass produced in an ecosystem CO_2 exchange	
	Flow of energy, matter, and information	Water retention	Flow of energy, matter, and information	
	Diversity and abundance of species	CO2 storage	Diversity and abundance of species	
		Food production		
		Natural resource production		
		Maintenance of physical, chemical, and biological conditions of the environment		
		Reduction of the risk of damages from, e.g., landslides, storms, or floods		

	Scales			
Dimensions	Country	Basin	Community	Household / Individuals
		Cultural services: enjoying outdoor activities in a pleasant setting and provision of biophysical basis for aesthetic, scientific, and educational values people hold for the continued existence of species and ecosystems		
		Flow of energy, matter, and information		
		Diversity and abundance of species		
Culture, justice, and peace	Internal and external migration	Internal and external migration	Internal and external migration	Migration

Table 4. Examples of condition for each dimension and scale

	Scales			
Dimensions	Country	Basin	Community	Household / Individuals
Health and wellbeing	Number of medicine students getting graduated per year	Medical doctor availability (# MD/100,000 inhab.)	Vaccination	Prior exposures Primary health
			Access to safe water for irrigation	Handwashing
				Access to safe water for human consumption
				Access to proper sanitation
				Open defecation
Infrastructure and associated services	Availability of technical staff for infrastructure maintenance	Maintenance of infrastructure	Maintenance of infrastructure	Training on maintenance of infrastructure
		Existence of advance treatment processes for antibiotic removal		
Economy and productivity	GDS	Income per river basin	Per capita income	Per capita income
		Income per river sub-basin		
Ecosystem services		Level on intervention: Aridity Land degradation Deforestation, land cover change		
		Conservation (people working on protection)		

	Scales			
Dimensions	Country	Basin	Community	Household / Individuals
		Regulation		
		Endemic, rare, and endangered species		
Culture, justice, and peace				

Table 5. Examples of resilience for each dimension and scale

	Scales			
Dimensions	Country	Basin	Community	Household / Individuals
Health and wellbeing	Endemic diseases	Endemic diseases	Food security	Underlying health
				Nutrition
				Water values
Infrastructure and associated services	Technical knowledge available	Design	Design	Design
	Availability of materials	Good materials	Good materials	Good materials
		Well-constructed	Well-constructed	Well-constructed
Economy and productivity	Dependency	Number of economic activities	Entrepreneurship knowledge	Entrepreneurship knowledge
Ecosystem services		Perturbation threshold that an ecosystem can stand before losing its equilibrium in biomass or energy	Perturbation threshold that an ecosystem can stand before losing its equilibrium in biomass or energy	
Culture, justice, and peace				

8 RISK ASSESSMENT

Risk will be determined for the consequences prioritised by stakeholders and, considering that water-security risks in river basins originate from complex systems interacting with each other through dynamic relationships in time and space, we may not quantify all risks. Instead, we can apply qualitative methodologies for complex risks, e.g., decision landscapes, boundary analysis, and characterisation of conceptual gateways or entry points (conceptual realms that are usually considered in isolation) (Schweizer et al., 2021). Such methodologies focus on the human category of systemic risks and treat closely the distortion of risk perception (attenuation or amplification)

(Schweizer et al., 2021). Figure 5 presents all the components of the risk assessment included in the MUISKA approach, including uncertainty, strength of knowledge analysis, and temporal considerations.

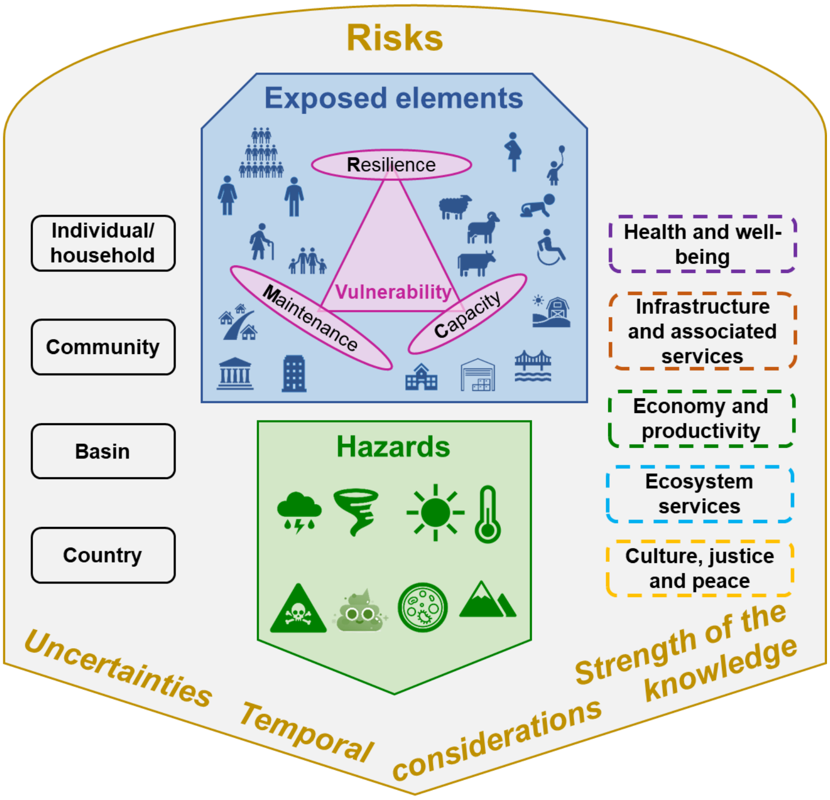


Figure 5. Representation of the risk characterisation by using the MUISKA approach

When possible, estimates of risk will be based on assessment of the scale and importance of hazard flows and the extent and depth of exposure within the affected population. Risk may be articulated in two general conceptual categories:

Population level risk relates to risks arising from direct human exposure (i.e., through drinking, eating, accidents, occupational health, loss of social assets, etc.) to quantifiable hazards (human and animal faecal wastes, agricultural and industrial runoff, micro pollutants, floods, droughts, and absence of water due to supply side failures).

Non population/societal level risks (or more correctly, risks for which we may not assign population level values) include direct damage to and loss of infrastructure and property, the development of AMR, depletion of fish stocks, decline in agricultural productivity, loss of amenity value, destabilisation of planning and budgeting processes, and vulnerability to major societal shocks such as 'natural disasters', pandemics.

Two predominant perspectives appear when discussing risks: the first one considers risk as exposure to a threat from quantitative methodologies; and the second, focuses on the sociocultural factors that influence people to identify a certain situation as risk (that is, their perception) (Global Challenges Research Fund Hub, 2020). In the current proposed methodology, we mainly treat risk as the product of the occurrence of a hazard and the exposure of the relevant scale (Table 2) given the hazard, and the expected damage given the vulnerability of the exposed scale (Aven, 2020). These three variables involved in risk calculation can also be expressed in terms of probabilities, but the risk analysts should provide the proper judgements of the strength of knowledge of such probabilities to recognise the limitations of the risk assessment (Aven, 2020) undertaken in river basins.

As Aven (2020) stated, how we define and characterise risks strongly determines the way we assess risk, then this poses important implications for risk management and decision making. Considering the importance of water security to all scales and dimensions considered here, clear definition of the risk concept and of the way to characterise it are essential steps for further risk assessment.

9 STANDARD METRIC TO INFORM ABOUT RISK IMPACTS

To inform about risk impacts, it is desirable to produce a standard metric that meets the needs of the decision makers (Aven, 2020). Risk analysts may consider several alternatives such as monetary assessments (economical losses and DALY's), qualitative categories (low, medium, high risk), or qualitative analysis by analytical hierarchical process to assign weights to risks and then expressing the values given by different stakeholders of a river basin. However, systemic risks cannot be easily characterised by single numerical estimations but can be assessed by using multiple indicators and including several dynamic gradients that can be aggregated into diverse but coherent scenarios (Renn et al., 2020).

We have examined this preliminarily with a group of the Colombian collaboratory (see chapter 12) and revealed that defining a standard metric to communicate risks could be one of the most challenging tasks in this research. During the work we did in June 2022 with this group, they contributed with the identification of risk indicators for the hazard "landslides", but we couldn't get a single standard metric that covers the whole spectrum of consequences of this hazard.

To respond to this tough challenge, the Hub Leeds team is leading a process to review scientific literature with more Hub members, who are experts in each of the five dimensions included in the current approach. This will help us determine how risk scientists and practitioners have conceptualised and applied risk indicators and to decide the best way to inform about risk impacts to decision makers.

10 RISK COMMUNICATION

The Society for Risk Analysis defines risk communication as the "*exchange or sharing of risk-related data, information and knowledge between and among different target groups (such as regulators, stakeholders, consumers, media, general public)*" (Society for Risk Analysis, 2018). In this line, we recommend that risk must be presented in a clear format and plain language to communicate effectively with dimensions outside academy and facilitate interventions and engagement with stakeholders. Initially, we suggest risks can be presented by visualisation tools such as spider charts (Figure 6), lollipop plots (Figure 7), Sanky diagrams (Figure 8), among others. Figure 4 is another example of how risks can be presented.

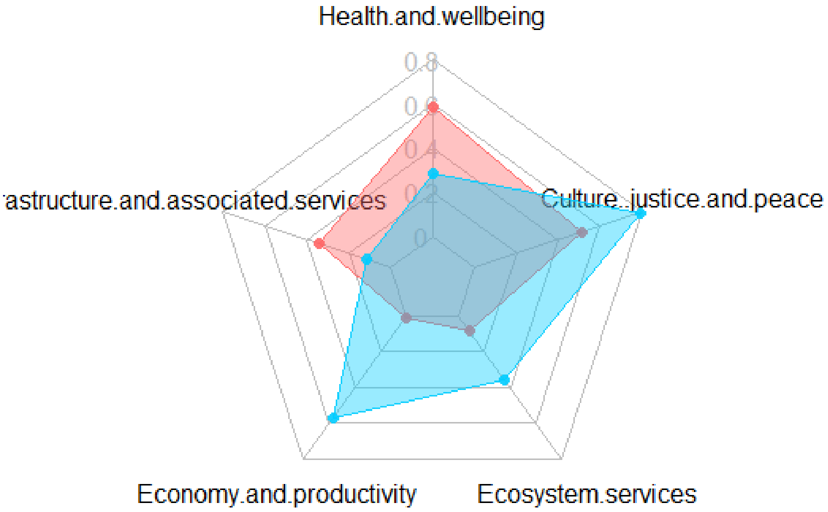


Figure 6. Example of a spider chart to represent risk classification at different dimensions in one scale

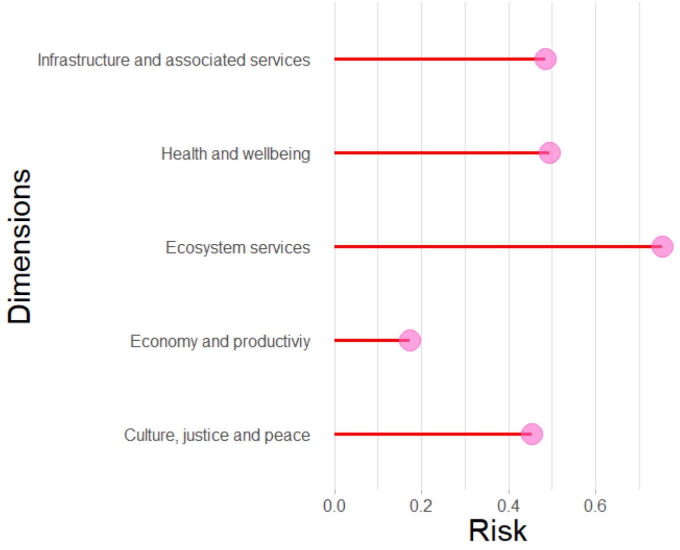


Figure 7. Example of a lollipop chart to represent risk classification at different dimensions in one scale

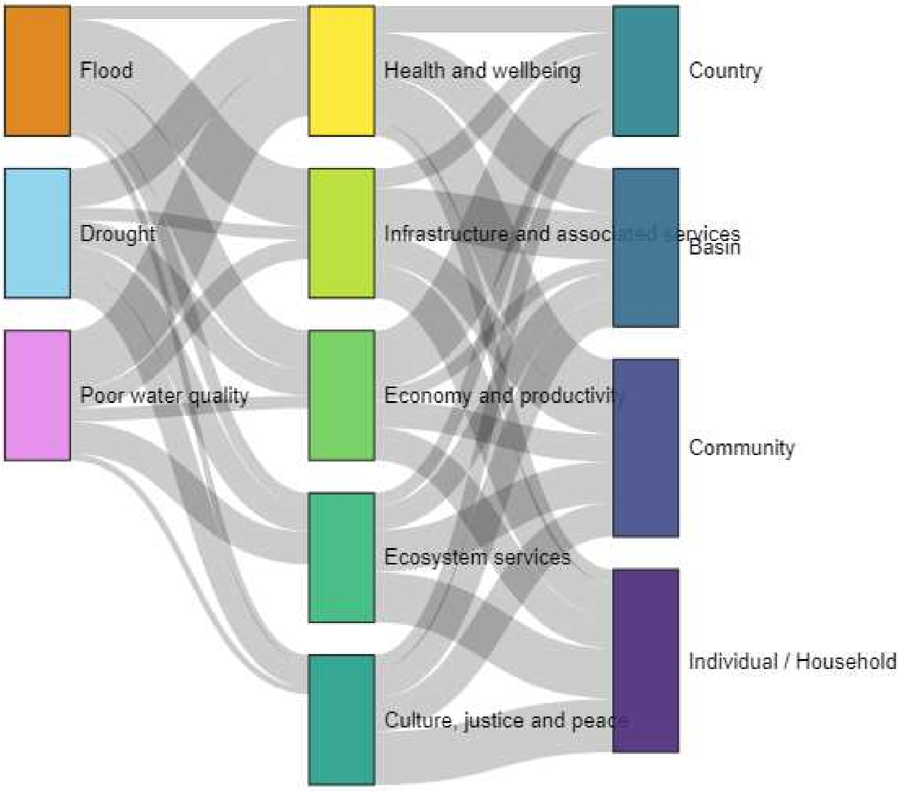


Figure 8. Example of a Sankey diagram to represent risk flow from dimensions to scales

Here, it is important to highlight that risk management is based on trust, then ethics and scientific quality of risk assessments are key to ensure validity of the risk assessment (Aven, 2020). By pursuing this, decision makers in charge of water security processes, who must handle other competing interests, can gather useful and valid information they need to develop their decisions. Involving stakeholders in risks assessments, including decision makers, brings a sense of realism and purpose (Hope, 2006), can help to build such trust, and could promote the incorporation of risk assessments for land and water planning.

11 HOW DOES MUISKA FIT IN THE WORK STREAM 3?

The MUISKA approach for water-security risk assessment in river basins is at the centre of the whole process in the W.S. 3, as Figure 9 shows it. The successful application of this approach highly depends on data availability. For this, the team in W.P. 3.1 designed a strategy to share primary and secondary data gathered by each collaboratory. However, it is possible that we require more detailed information to proceed with the step 4 in MUISKA (section 3.2).

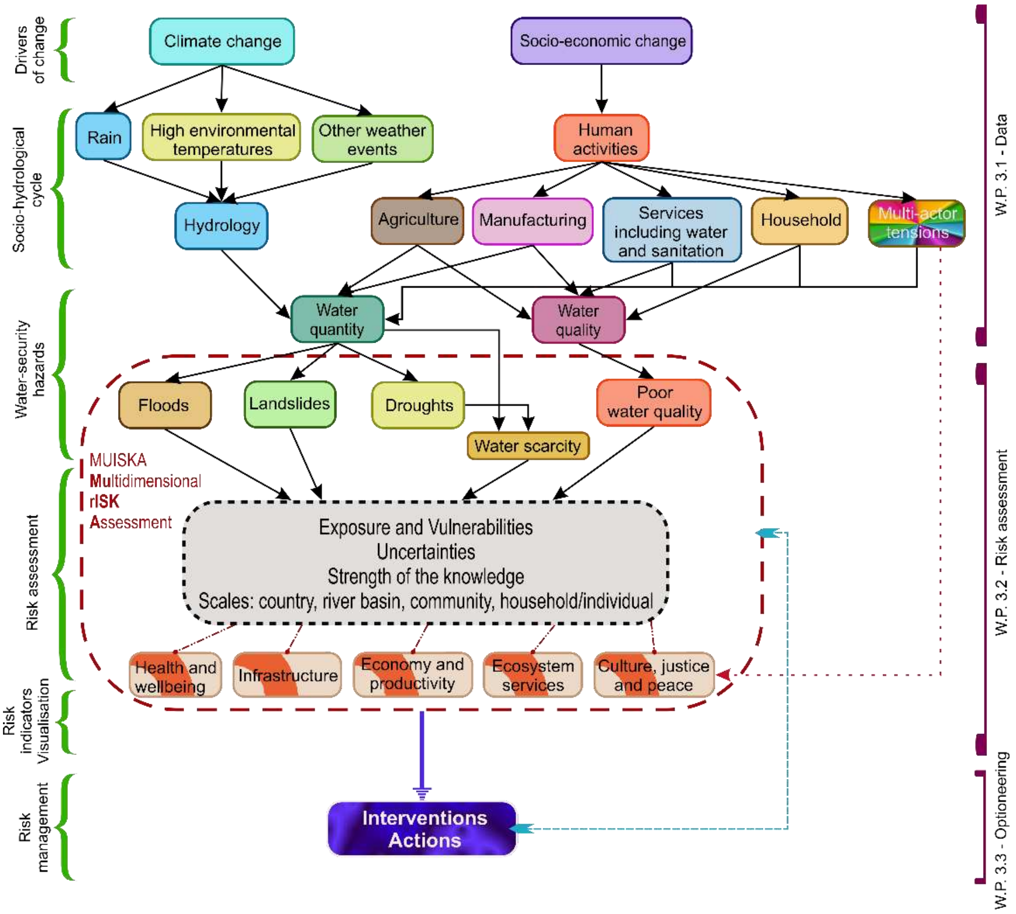


Figure 9. MUISKA within the W.S. 3

As a result of applying the MUISKA approach, we could enlighten some interventions or actions as part of the outline of a risk management plan in consultation with stakeholders. Thus, the team in W.P. 3.3 will have some additional inputs to work on optioneering solutions for development.

Figure 9 also helps to identify ways to communicate water-security risks to move forward to the phase of risk management, which is related to the Chapter 10 in this document. We, as the team working on the W.P. 3.2, are already designing a process to review scientific literature to identify risk indicators that scientists and practitioners have proposed or used to communicate water-security risks to stakeholders and other academics.

12 MUISKA IN SPECIFIC CONTEXTS

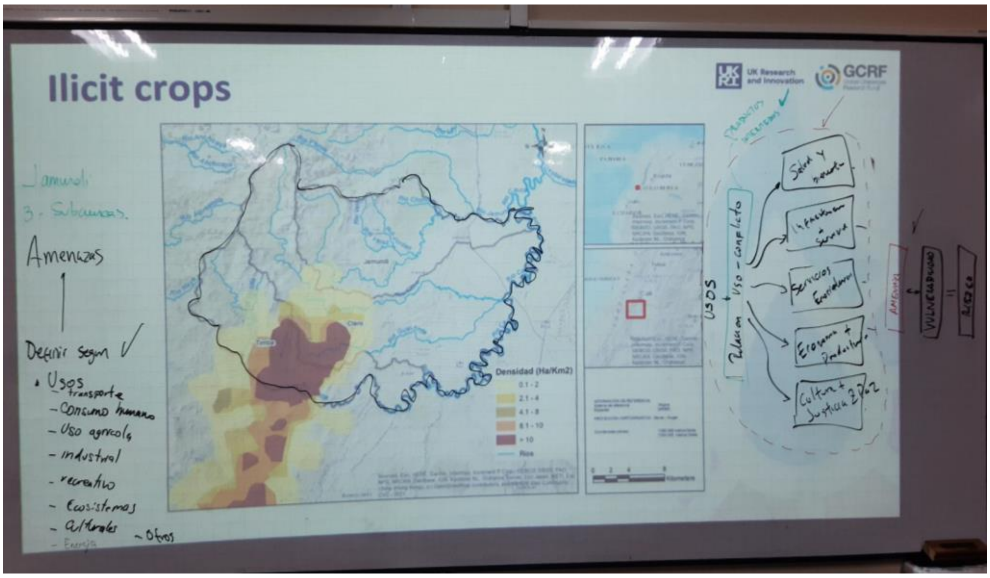
We are proposing MUISKA as a general approach to assess water security risks at different scales in any river basin. Researchers and practitioners can also adapt MUISKA to specific local contexts. Therefore, we will run a pilot in the municipalities Cajibío and Jamundí to fully develop MUISKA. Cajibío and Jamundí are at the Upper Cauca River Basin (UCRB), where our Hub partners from the Colombian collaboratory are conducting research on water security. For this, we undertook preliminary in-person activities with a group from this collaboratory to socialise this approach and discuss local context conditions and potential challenges we may face to communicate risks.

From such activities, the participants discussed and agreed on adjusting MUISKA according to the specific conditions of the UCRB. First, increased rates of urbanisation could lead to water scarcity. Despite this is not specified in Figure 9, urbanisation is one of the socio-economic drivers to be considered in the lilac block at the left top of this figure. Another particularity of the Colombian context is the existence of an armed conflict with different illegal actors and where civil society is left facing multiple life threats. Thus, Figure 9 represents this situation as multi-dimension tensions to account also for other disputes, frictions, and conflicts.

For the case of the UCRB, illegal groups in the sub-river basin Jamundí, who produce narcotics, cause that a rural aqueduct operates intermittently by losing water through the headrace pipeline. They use that water on their crops and production process. Landslides were also included (Figure 9) because of this is a common situation in the Andean region when heavy rain falls on saturated soils. These can affect water infrastructure such as headrace pipelines, water treatment plants, water distribution networks, sewages, and wastewater treatment plants.

The group also discussed the term “hazard”, which has a negative connotation due to it means something is dangerous. However, some UCRB communities understand some hazards as the opposite: something they desire. For example, the community from Bocas del Palo thinks about floods as “the river is visiting us” because the river fills their lands with nutrients.

The group also examined how MUISKA should be developed through in-person interactions with river basin stakeholders and then "translate" those outcomes into the MUISKA's structure (see section 3.2). For this, we agreed on talking with the participants about how individuals and communities use water daily. Then, ask them to describe any problem arising from those water uses, create the consequences network per each problem and classify them on the five dimensions established in our approach (Photograph 1). Then we will continue with the step 3 thereafter.



Photograph 1. Examination on MUISKA development by in-person activities with stakeholders

The preliminary in-person work with the Colombian group suggests MUISKA is a workable process to assess water-security risks in river basins and it can be shaped according to the local conditions where it will be developed.

13 INTEGRATED WATER RESOURCE MANAGEMENT AND OUR METODOLOGY

GCRF Hub is mainly based on Sustainable Development Goal (SDG) No. 6: "*Ensure availability and sustainable management of water and sanitation for all*." In the SDG6 Synthesis Report, it is described how SDG6 interacts with most of the other SDGs (12 out of 16) as shown in Figure 10 and Table 6. This features how dimensions are in some way related to water resources and support definitions of water security, which incorporate the participation of multiple categories and our argument about that water-security risks should be approached from the system thinking theory (Meadows, 2008).

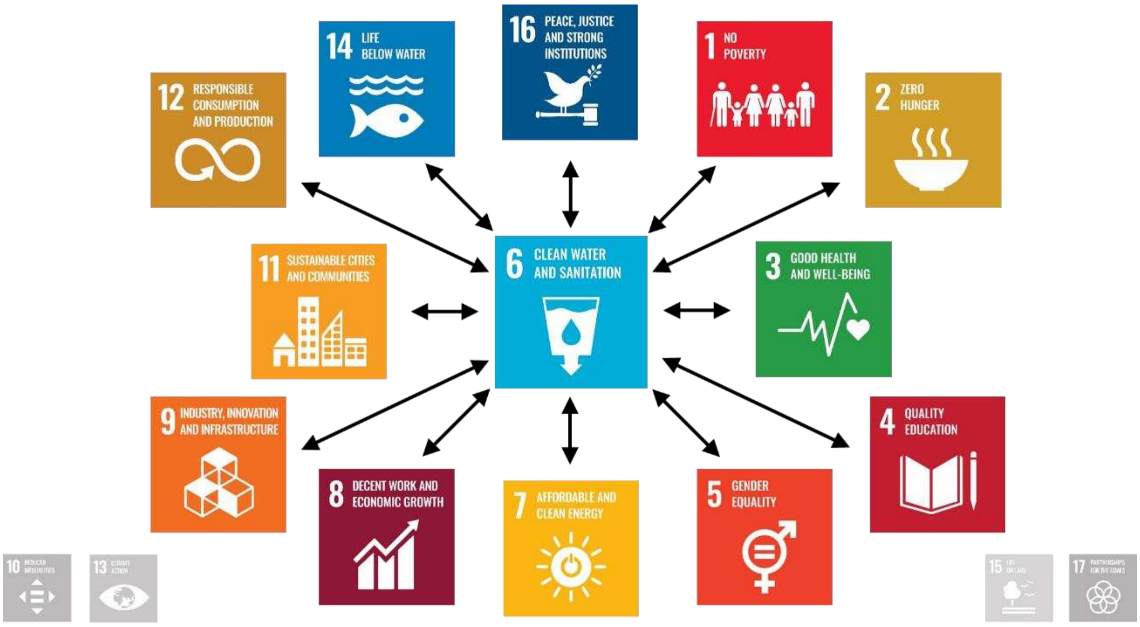


Figure 10. SDG interactions

Table 6. Interactions of SDG6 with other SDGs

Other SDGs	Interaction
SDG1	Water-related diseases are closely linked to poverty, and disproportionately affect vulnerable communities that do not have access even to basic sanitation services.
SDG2	1. 70% of water abstractions are for food security. 2. Pollutants affecting water quality occur because of agriculture (SDG2), industry (SDGs 9 and 12), energy production, and extractive processes (SDG7).
SDG3	Access to sanitation reduces environmental pollution (including water-borne pathogens) and its health impacts.
SDG4	Improving access to WAS I in schools can enhance pupil and teacher health, school attendance and welfare, which benefits educational outcomes for all.
SDG5	In 61 countries, women and girls are responsible for water collection in 80% of households.
SDG7	Pollutants affecting water quality occur because of agriculture (SDG2), industry (SDGs 9 and 12), energy production and extractive processes (SDG7).
SDG8	1.4 billion jobs rely on water.
SDG9	3. Pollutants affecting water quality occur because of agriculture (SDG2), industry (SDGs 9 and 12), energy production and extractive processes (SDG7). 4. 81% of companies rely on freshwater for their operations.
SDG11	Cities and towns present a major water challenge, as they are expected to be home for some 66 percent of the world's population by 2050. Cities do not function in isolation; they exist within river basins and what happens in cities affects others downstream and vice versa.
SDG12	Pollutants affecting water quality occur because of agriculture (SDG2), industry (SDGs 9 and 12), energy production and extractive processes (SDG7).
SDG14	Water-security ecosystems are increasingly under threat, as the demand grows for fresh water for agriculture, energy, and human settlements.
SDG16	Target 6.5 of SDG6 explicitly demands transboundary cooperation over natural resources management. Achieving it will have wide-ranging benefits, such as supporting culture, justice, and peace at national and international levels.

Source: Adapted from UN-Water (2018) *and Global Challenges Research Fund Hub (w.d)*

The SDG6 includes eight targets and target 6.5 specifies that "*by 2030, implement integrated water resources management at all levels, including through transboundary cooperation as appropriate*" (Figure 11) and United Nations (UN) considers that progress on this will arguably be the most comprehensive step countries can make towards achieving SDG6 (UN-Water, 2018). In this line, the Global Water Partnership (GWS), a global action network with over 3,000 partner organisations in 179 countries, has established a framework for Integrated Water Resource Management (IWRM), whose principles must be recognised by GWS partners. Accordingly, GWS (2020) defined IWRM as "*a process which promotes the coordinated development and management of water, land and related resources in order to maximise economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems.*"

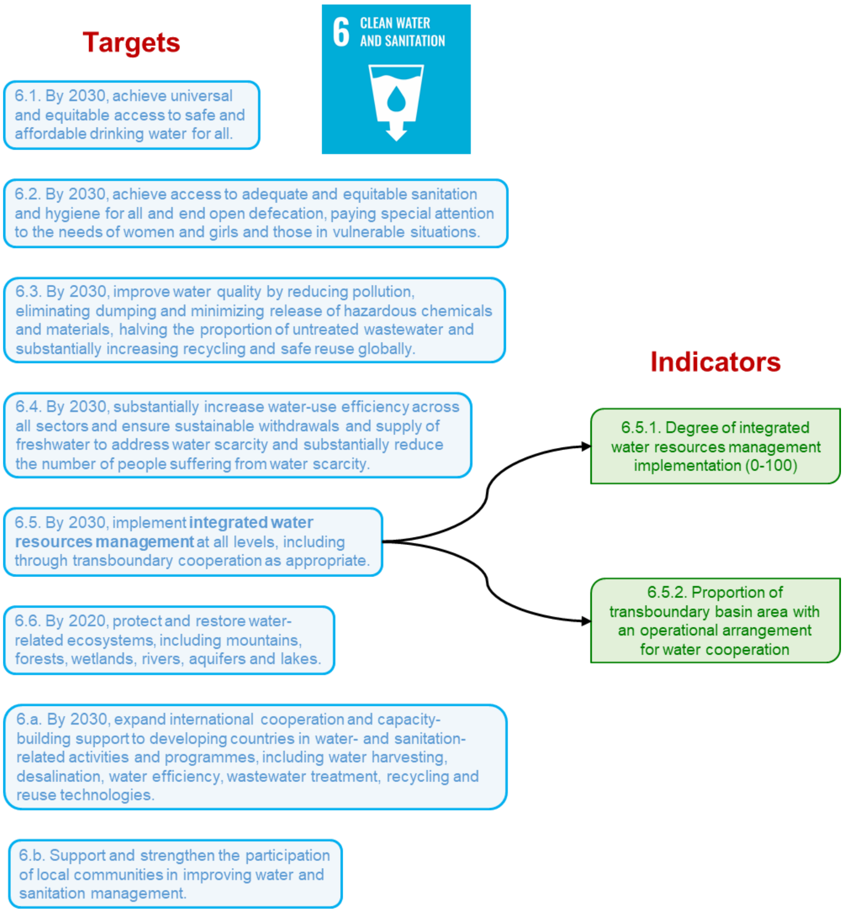


Figure 11. Sustainable development goal 6 and GCRF Hub

Target 6.5 of the SDG6 explicitly advocates for formulation and implementation of IWRM in river basins (Figure 11). However, 129 countries and territories are not on track to meet target 6.5 (Figure 11) by 2030 and, according to data from 2017 and 2020, only approximately 16% (24 out of 153) of countries and territories that share transboundary rivers, lakes, and aquifers have totally covered their transboundary basin area by operational arrangements, and only another 22 countries and territories have over 70% covered (Economic and Social Council UN, 2021). Considering that stakeholders working on water security across dimensions widely accepted this approach, we consider relevant to discuss further the similarities and differences between IWRM framework proposed by GWS (Global Water Partnership, 2018) and the current methodology.

Table 7 compares both approaches in five categories: basis, incorporation of risk approach, scales, dimensions, and communication. In essence, IWRM is a framework oriented towards the provision of solutions to decision makers by formulating and implementing new regulations for water policy and management and risk assessments are included as one of instruments proposed for water management. We root our methodology in risk science for making a risk assessment in complex water systems by analysing systemic risks. Initially, we will resort to Hub members from different disciplines to get their feedback on the current proposal, then we will employ their expertise for risk assessment, and will validate the adjusted methodology and results on the field to involve other stakeholders. Our ultimate aim is to produce information for guiding decision makers and stakeholders able to influence decision making. MUISKA approach may contribute to achieve IWRM.

Table 7. Comparison between IWRM and our methodology

Category	MUISKA approach	IWRM approach
Basis	Approach to curate information and compare risks. A tool to achieve IWRM and guide decision makers.	Process for government-related people to negotiate their preferred policy interventions.
	Recognise the importance of including sufficient stakeholders in risk assessment and acknowledge their capacity to influence decision making.	Aimed to maximise economic and social welfare.
Incorporation of risk approach	Based on risk science and risk assessment methods.	Instrument for management included in the thematic area "Management instruments".
	Vulnerability is part of the risk assessment of four scales in five dimensions.	Vulnerability assessment is associated with climate change.
	Resilience is included as a component of vulnerability.	Advocate for examination of resilience of subsystems to increase the coping capacities of such subsystems.
	Social aspects are represented by scales and ecosystems, economy, wellbeing, and culture, justice, and peace are considered dimensions.	Social, ecosystem, environmental impact, and economic assessments are included as management instruments at the same level of risk assessments.
	Uncertainty and ambiguity are recognised as characteristics of	Uncertainty and ambiguity are not mentioned.

Category	MUISKA approach	IWRM approach
	systemic risks present in complex systems like river basins. Scenarios can cope with uncertainty. Besides hazards and vulnerability, risk assessment also includes the judgements of the strength of knowledge supporting the risk assessment.	
Scales	Four scales are included to acknowledge that risks do not impact to all in the same way: country, river basin, community, and household/individuals.	Populations, communities, institutions, families, and individuals are included in social assessments.
Dimensions	Five dimensions are incorporated to identify the consequences and their magnitude: health and wellbeing, infrastructure, economy and productivity, ecosystems and ecosystem services, and culture, justice, and peace.	Economic assessments are included as a tool to monetise impacts and benefits to recommend the most suitable water project. The possibility of arousing conflictive interests among local, regional, and national decision makers is not recognised.
Communication	Risk communication recognises risk perception and water values.	Recognise that communication is necessary for meaningful involvement of stakeholders in the decision-making and implementation process.

Adapted from Global Water Partnership (2018)

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15 APPENDIX A. GLOSSARY

Capacity

For elements different from human beings, capacity refers to the amount of material components that such element can hold. For example, the maximum amount of water that a bridge allows to flow through without being dragged.

With human beings, capacity can be understood in the current conceptual framework as the ability to cope with continuous, frequent, or unusual hazards due to acquired resources through a lifetime. For example, a completed vaccine programme helps to reduce vulnerability to infectious diseases in children and adults.

Condition

Condition is directly related to maintenance of each element executed from someone external to that element periodically. For example, bridges must be checked regularly to prevent structure erosion and further failing. The availability of an appropriate number of medical doctors to attend population needs indicates people can get opportune health services and keep good physical and mental conditions.

Dimension

Five dimensions are included as subsets of the whole network of complex interrelationships between hazards and risks in a river basin. The creation of these subsets does not mean ignoring the complex nature of a basin system but will allow to assess risks in a focused manner.

Drought

Meteorological drought happens when dry weather patterns dominate an area. It can begin and end rapidly[1].

Hydrological drought occurs when low water supply becomes evident, especially in streams, reservoirs, and groundwater levels, usually after many months of meteorological drought. It takes much longer to develop and then recover[2].

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[1] National Centers for Environmental Information. (n.d.). *Definiton of drought*. Retrieved November 24, 2021, from https://www.ncdc.noaa.gov/monitoring-references/dyk/drought-definition

[2] National Centers for Environmental Information. (n.d.). *Definiton of drought*. Retrieved November 24, 2021, from https://www.ncdc.noaa.gov/monitoring-references/dyk/drought-definition

Agricultural drought happens when crops become affected[3].

Socioeconomic drought relates the supply and demand of various commodities to drought[4].

Ecological drought arises when ecosystems are affected[5].

Exposure

It is the situation of people, infrastructure, housing, production capacities, and other tangible human assets in hazard-prone areas. Measures of exposure can include the number of people or types of assets in an area.[6]

Flood

It occurs when an overflow of water submerges land that is usually dry. Heavy rainfall, rapid snowmelt or a storm surge often causes floods from a tropical cyclone or tsunami in coastal areas[7].

Hazard

Hazards are risk sources where the potential consequences relate to harm. Hazards could, for example, be associated with energy (e.g., explosion, fire), material (toxic or eco-toxic), biota (pathogens) and information (panic communication)[8].

In water systems, hazards are physical, biological, chemical, or radiological agents or hazardous events that can cause harm to exposed scales.[9] For example, a contaminated water source with protozoa may affect negatively public health if such water is being consumed without proper treatment. A heavy rain event may lead to floods in a village, damaging its infrastructure.

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[3] National Centers for Environmental Information. (n.d.). *Definiton of drought*. Retrieved November 24, 2021, from https://www.ncdc.noaa.gov/monitoring-references/dyk/drought-definition

[4] National Centers for Environmental Information. (n.d.). *Definiton of drought*. Retrieved November 24, 2021, from https://www.ncdc.noaa.gov/monitoring-references/dyk/drought-definition

[5] National Integrated Drought Information System. (n.d.). *Drought basics*. Retrieved November 24, 2021, from https://www.drought.gov/what-is-drought/drought-basics

[6] Open Risk Manual. Available on: https://www.openriskmanual.org/wiki/Exposure.

[7] World Health Organization. (2021). Floods. https://www.who.int/health-topics/floods#tab=tab_1

[8] Society for Risk Analysis. (2018). Society for Risk Analysis Glossary (p. 9). https://www.sra.org/wp-content/uploads/2020/04/SRA-Glossary-FINAL.pdf

[9] Bartram, J., Corrales, L., Davison, A., Deere, D., Drury, D., Gordon, B., Howard, G., Rinehold, A., & Stevens, M. (2009). Water safety plan manual: step-by-step risk management for drinking-water suppliers. World Health Organization.

Hydrocomplexity

An integrated approach, aimed at taking a broad contextual view of water in all its complexity to seek principles and methodologies to unravel the interactions across hydrosphere, biosphere, atmosphere, cryosphere, lithosphere, and anthroposphere[10].

Interdisciplinarity

Interdisciplinarity is the combining of methods and insights of two or more academic disciplines into pursuing a common task. It is typically characterised by the crossing of ‘traditional boundaries’ between academic disciplines or schools of thought to address new and emerging issues. Often, interdisciplinarity is applied where traditional disciplines cannot address the problem. It can likewise be applied to complex subjects that can only be understood by combining the perspectives of two or more fields[11].

Judgements of the strength of the knowledge

Any judgement of uncertainty is based on some knowledge K, and this knowledge can be more or less strong. According to Aven (2020), the judgement of the strength of the knowledge can be reported in this section like this:

“*The knowledge K is judged as weak if one or more of the following conditions are true:*

1. *The assumptions made represent strong simplifications.*
2. *Data/information are/is non-existent or highly unreliable/irrelevant.*
3. *There is strong disagreement among experts.*
4. *The phenomena involved are poorly understood; models are non-existent or known/believed to give poor predictions.*
5. *The knowledge has not been examined (for example, with respect to unknown knowns).*

If, on the other hand, all (whenever they are relevant) of the following conditions are met, the knowledge is considered strong:

6. *The assumptions made are seen as very reasonable.*
7. *Large amounts of reliable and relevant data/information are available.*

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[10] Kumar, P. (2015). Hydrocomplexity: Addressing water security and emergent environmental risks. *Water Resources Research*, *51*(7), 5827–5838. https://doi.org/https://doi.org/10.1002/2015WR017342

[11] University of Warwick. (2019). Interdisciplinarity. https://warwick.ac.uk/fac/cross_fac/academy/keythemes/interdisciplinarity/

8. There is broad agreement among experts.
9. The phenomena involved are well understood; the models used are known to give predictions with the required accuracy.
10. The knowledge K has been thoroughly examined.

Cases in between are classified as medium strength of knowledge."

Resilience

It is the capacity of social, economic and ecosystems to cope with a hazardous event or trend or disturbance, responding or reorganising in ways that maintain their essential function, identity, and structure as well as biodiversity in case of ecosystems while also maintaining the capacity for adaptation, learning and transformation. Resilience is a positive attribute when it maintains such a capacity for adaptation, learning, and/or transformation[12]. It is important to consider that such essential function, identity, and structure is system and context specific. Also, if the capacity for adaptation, learning and transformation was not enough before the hazardous event, then it will be weakened even more after this and the system will need more support for effective adaptation, learning and transformation to a desired functionality[13].

Risk

The mental concept that exists when considering an activity in the future and involve two main features: i) values at stake (consequences regarding something that humans value) and ii) uncertainties (what will the consequences be?)[14].

Two predominant perspectives appear when discussing risks: the first one considers risk as exposure to a threat from quantitative methodologies; and the second, focuses on the sociocultural factors that influence people to identify a certain situation as risk

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[12] IPCC - Intergovernmental Panel on Climate Change. (2022). Climate Change 2022: Impacts, Adaptation and Vulnerability. In H.-O. Pörtner, D. C. Roberts, M. Tignor, E. S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, & B. Rama (Eds.), Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (p. 3068). https://doi.org/10.1017/9781009325844

[13] Logan, T. M., Aven, T., Guikema, S. D., & Flage, R. (2022). Risk science offers an integrated approach to resilience. Nature Sustainability, 5(9), 741–748. https://doi.org/10.1038/s41893-022-00893-w

[14] Aven, T. (2020). The Science of Risk Analysis: Foundation and Practice (1st ed.). Routledge. https://doi.org/10.4324/9780429029189

(that is, their perception). For this last perspective, qualitative methodologies are mainly proposed[15].

Risk assessment

A systematic process to comprehend the nature of risk, express and evaluate risk, with the available knowledge.[16]

Risk domains

Risk domains include the proposed dimensions and scales proposed in the MUISKA approach order to assess multiple water-security risks.

Systemic risks

A systemic risk must meet the following conditions: high complexity regarding causal or functional relationships (no linear cause-effect relationship but multiples negative and positive feedback loops instead), multiple uncertainties, being associated with cascading impacts within the scale in which the risk is located and beyond this scale, and major ambiguities[17]. Systemic risks are also characterised by high dependency on contextual factors[18]. Interdisciplinarity is necessary to develop approaches to study the emergent dependencies present when studying complex water systems[19].

Vulnerability

Inherent property of the scale exposed to a hazard related to a weakness, attribute, cause or lack of control, which would allow to hazards to cause harms[20].

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[15] Global Challenges Research Fund Hub. (2020). W.S. 3 Risk abstract (p. 7). https://3.basecamp.com/4218703/buckets/12110354/uploads/3139277702

[16] Aven, T. (2020). The Science of Risk Analysis: Foundation and Practice (1st ed.). Routledge. https://doi.org/10.4324/9780429029189

[17] Renn, O., Laubichler, M., Lucas, K., Kröger, W., Schanze, J., Scholz, R. W., & Schweizer, P.-J. (2020). Systemic Risks from Different Perspectives. Risk Analysis, n/a(n/a). https://doi.org/https://doi.org/10.1111/risa.13657

[18] Schweizer, P.-J., Goble, R., & Renn, O. (2021). Social Perception of Systemic Risks. Risk Analysis, 0(0). https://doi.org/https://doi.org/10.1111/risa.13831

[19] Kumar, P. (2015). Hydrocomplexity: Addressing water security and emergent environmental risks. Water Resources Research, 51(7), 5827–5838. https://doi.org/https://doi.org/10.1002/2015WR017342

[20] Función Pública. (2018). Guía para la administración del riesgo y el diseño de controles en entidades públicas.

Water security

There are several definitions of water security and we included mainly these two definitions:

Water security, at any level from the household to the global, means that every person has access to enough safe water at affordable cost to lead a clean, healthy and productive life, that the vulnerable are protected from the risks of water-security hazards while ensuring that the natural environment (freshwater, coastal and related ecosystems) is protected and political stability is promoted. Those using and sharing river basins and aquifers must manage their water sustainably, balancing water use for human development with protection of vital eco-systems and the ecological services they provide[21,22].

Water security is the capacity of a population to safeguard access to adequate quantities of water of acceptable quality for sustaining human and ecosystem health on a watershed basis, and to ensure efficient protection of life and property against water related hazards (floods, landslides, land subsidence, and droughts). Water security should be developed in a climate of peace and political stability[23,24].

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[21] Global Water Partnership. (2000). Towards Water Security: A Framework for Action. World Water Council.

[22] Ministers and Heads of Delegation. (2000). Ministerial Declaration of The Hague on Water Security in the 21st Century, Second World Water Forum 22nd March. https://www.worldwatercouncil.org/fileadmin/world_water_council/documents/world_water_forum_2/The_Hague_Declaration.pdf

[23] Donoso, M., Di Baldassarre, G., Boegh, E., Browning, A., Oki, T., Tindimugaya, C., Vairavamoorthy, K., Vrba, J., Zalewski, M., & Zubari, W. K. (2012). International Hydrological Programme (IHP) eighth phase: Water security: responses to local, regional and global challenges. Strategic plan, IHP-VIII (2014-2021). https://rucforsk.ruc.dk/ws/portalfiles/portal/49711492/2012_IHP_VIII.pdf

[24] UN-Water. (2013). Water Security & the Global Water Agenda. A UN-Water Analytical Brief. https://www.unwater.org/publications/water-security-global-water-agenda/

16 APPENDIX B. EXAMPLES OF RISKS CLASSIFIED BY DIMENSIONS AND SCALES

Table A. Examples of risks in each intersection of dimension – scale of the matrix of risk domains considered in the MUISKA approach

	Hazardous event	**Scales**			
Dimensions		Country	Basin	Community	Household / Individuals
Health and wellbeing	Consumption of contaminated water with pathogens	Increased demand for physicians	Stressed medical institutions	Increased cases of acute diarrhoeal disease	Cases of acute diarrhoeal disease
				Increased demand for medicines	Increased demand for medicines
					Increased stress
	Flood	Increased demand for physicians, psychologists, and psychiatrists	Scarcity of physicians, psychologists, and psychiatrists	Increased cases of disability	Disability
			Stressed medical institutions	Increased cases of deaths	Deaths
			Increased demand for rescue service staff: fireperson, police person, Cross Red, etc.	Increased cases of physical and mental diseases	Bad physical and mental health
					Malnutrition
	Discharges of antibiotics to water bodies	Exposed to AMR organisms	Exposed to AMR organisms	Exposed to AMR organisms	Exposed to AMR organisms
		Increased cases of deaths associated with AMR diseases	Increased cases of deaths associated with AMR diseases	Increased numbers of infectious diseases related to AMR	Increased numbers of infectious diseases related to AMR
Infrastructure and associated services	Consumption of contaminated water with pathogens	Increased demand for pipelines, fittings, and chemicals for cleaning and corrective maintenance of affected water supply systems	Contamination of water treatment plants, public pipelines, storage tanks, service reservoirs	Contamination of water treatment plants, public pipelines, storage tanks, service reservoirs	Contamination of domestic pipelines and storage containers
	Flood	Destroyed bridges and roads that communicate the affected region with others	Destroyed bridges, buildings, and houses; broken water and sewage pipes, and electricity and telecommunication infrastructure.	Destroyed bridges and roads and sewage pipes, and electricity and telecommunication infrastructure.	Destroyed houses

Dimensions	**Hazardous event**	**Scales**			
		Country	Basin	Community	Household / Individuals
			Increased demand for safe shelters		Houses cannot be inhabited
	Discharges of antibiotics to water bodies	Growing demand for advanced treatment processes to remove antibiotics from domestic wastewater	Need to incorporate advanced treatment processes to remove antibiotics from domestic, healthcare facilities and antibiotic manufacturer wastewater in existing or projected treatment plants.	Need to increase knowledge on operation and maintenance of advanced processes to remove antibiotics from wastewaters.	Need to take training on operation and maintenance of advanced processes to remove antibiotics from wastewaters.
		Growing demand for advanced treatment processes to remove antibiotics from wastewater produced in healthcare facilities			
		Growing demand for advanced treatment processes to remove antibiotics from wastewater produced in healthcare facilities			
Economy and productivity	Consumption of contaminated water with pathogens	Reduced circulation of goods and foods	Reduced economic activities	Reduced economic activities	Reduced household incomes
		More funds required to support medical services	Reduced basin incomes	Reduced community incomes	
		Reduced society incomes			
	Flood	Loss or delay of socio-economic development	Loss or reduced production of goods, food, and services	Loss or reduced economic transactions	Loss or reduced household incomes
		Increased insurance costs	Increased food prices	Reduced community incomes	

		Scales			
Dimensions	**Hazardous event**	Country	Basin	Community	Household / Individuals
		Good and service shortage	Food shortage		
		More funds required to support medical services	Reduced basin incomes		
		Reduced society incomes			
		Endangered cultural and ethnic diversity			
	Discharges of antibiotics to water bodies	Increased costs in healthcare expenditures	Loss of jobs	Reduced incomes	Reduced incomes
		Worktime and productivity losses	Worktime and productivity losses	Loss of jobs	Loss of jobs
		Increased costs in the agricultural dimension	Increased costs in the agricultural dimension		
Ecosystem services	Consumption of contaminated water with pathogens	Contamination of other connected river basins	Reduced dissolved oxygen	Discharges of wastewater to water bodies	Discharges of wastewater to water bodies
		Loss of trust in institutions	Increased pathogen loads downstream discharges		
			Alteration of water species balance		
			Loss of biodiversity		
	Flood	Peak contamination of other connected river basins	Alteration of land ecosystems	Alteration of land ecosystems	Broken relationship between humans and ecosystems
		Endangered cultural and ethnic diversity	Increased deaths of aquatic higher-level species	Alteration of aquatic ecosystems	
			Increased load of suspended solids		
	Discharges of antibiotics to water bodies	Increased animal mortality rates	Increased animal mortality rates	Discharges of wastewater with AMR organisms to water bodies	Discharges of wastewater with AMR organisms to water bodies
		Loss of biodiversity	Loss of biodiversity		
	Consumption of contaminated water with pathogens		Reduced ways to use water	Poor water quality for human consumption and scenic and recreational use	Poor water quality for human consumption and scenic and

Dimensions	**Hazardous event**	**Scales**			
		Country	Basin	Community	Household / Individuals
					recreational use
			Reduced seafood production		
	Flood	Increased accumulation of sediments in dams	Increased demand for safe areas to build shelters		
			Reduced touristic activities		
			Wash fertile soil out		
	Discharges of antibiotics to water bodies	Increased animal mortality rates	Increased animal mortality rates	Increased mortality rates of farm animals	Increased mortality rates of farm animals
Culture, justice, and peace	Consumption of contaminated water	Conflictive relationships between national, regional, and local surveillance health authorities	Conflictive relationships between surveillance health authorities and water utilities	Increased student absence	Conflictive relationships among water utilities and consumers
		Increased demand of technical capacity to attend waterborne disease outbreaks	Conflictive relationships between local and regional surveillance health authorities	Conflictive relationships among local surveillance health authorities, water utilities and communities	
	Flood	Loss trust in institutions	Isolated communities, towns, villages, and municipalities	Broken communities	Broken families
				Displaced communities	Increased domestic violence
					Increased number of orphans
	Discharges of antibiotics to water bodies	Increased transnational conflicts due to AMR presence in one territory and AMR diseases appear in another territory	Increase of conflicts between affected population and national and regional health authorities	Increase of conflicts between affected population and local health authorities	Increase of conflicts between affected population and local health authorities

17 APPENDIX C. EXAMPLE OF A MIND MAP TO REPRESENT THE NETWORK OF HAZARDS AND THEIR CONSEQUENCES

Figure A shows an example of the network created for the hazard “hydrological drought” and its consequences in a river basin. The items highlighted with yellow colour indicates those which were outside of the expertise or knowledge of the people who created this network.

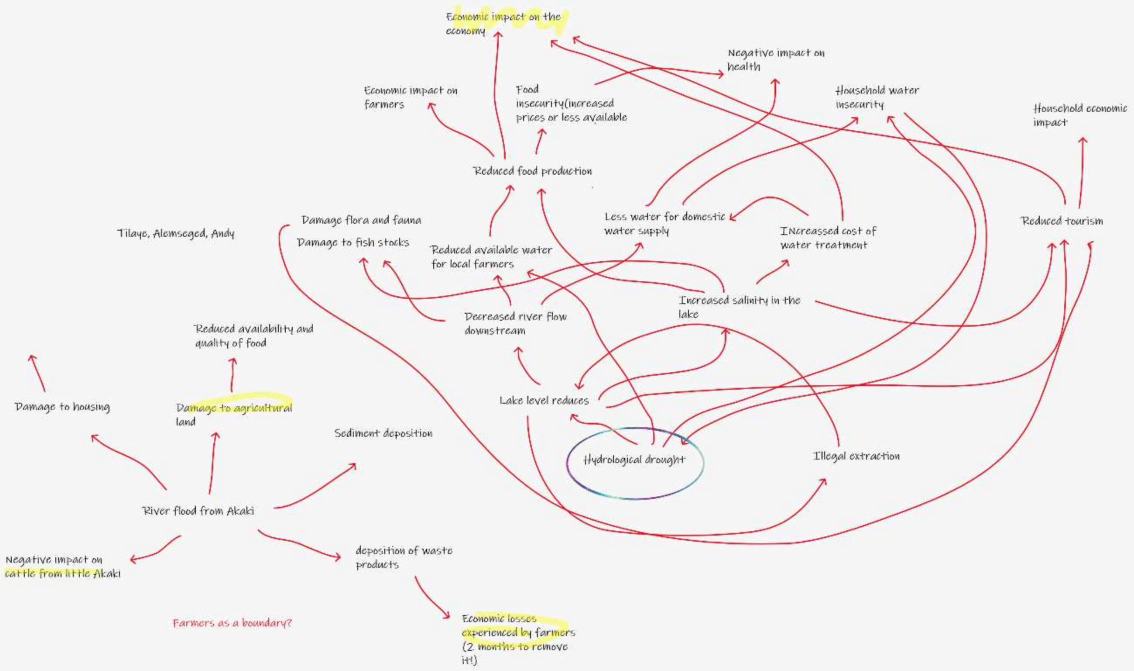

Figure A. Network of one hazard and its consequences

Source: Group meeting with the group working on Ethiopian river basins