A Drought and Heat Risk Assessment Framework for Urban Green Infrastructure

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Abstract

Urban green infrastructure (UGI) is a prominent concept towards climate adaptation and urban resilience, but is also affected by droughts and heat. Hence, this study aims to advance the multi-assessment of drought and heat risks for UGI through a framework with conceptual and methodological features, paving the way towards knowledge creation and decision support. The framework was systematically developed, starting with defining the situation, analyzing concepts, and finally, constructing the framework. The situation is interpreted as a Coupled Human and Natural System to represent the biophysical and immaterial elements, processes and interrelations. Further, the concepts of risk, UGI and ecosystem services come together in a risk system showing the compound hazards, the exposure, and the cascading vulnerabilities of the UGI. The drought and heat risk assessment framework distinguishes two stages, multi-risk analysis, and multi-criteria risk evaluation. The analysis includes definition and interpretation of the UGI situation under drought and heat conditions, analyzing the hazards, exposure, and vulnerabilities of the system, and translating the risk system into an indicator-based information system. Hereby, the vulnerability analysis of the biophysical UGI aspects comprises the susceptibility and resilience of UGI entities, as well as the degree to which providing ecosystem functions and services can be affected. The multi-criteria risk evaluation covers the assignment of thresholds and weights for indicators, in addition to the aggregation methods. The resulting framework intends to support local actors in the risk assessment of current and future conditions, fostering evidence-based decisions and interventions to deal with risks.

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Key Points:

- The drought and heat situation for urban green infrastructure is systematically conceptualised, considering coupled human and natural aspects.
- The risk system includes the vulnerabilities of urban green infrastructure's entities, their ecosystem functions, and ecosystem services.
- The assessment framework provides conceptual and methodological procedures to analyze and evaluate the multi-risks for urban green infrastructure.

Abstract

Urban green infrastructure (UGI) is a prominent concept towards climate adaptation and urban resilience, but is also affected by droughts and heat. Hence, this study aims to advance the multi-assessment of drought and heat risks for UGI through a framework with conceptual and methodological features, paving the way towards knowledge creation and decision support. The framework was systematically developed, starting with defining the situation, analyzing concepts, and finally, constructing the framework. The situation is interpreted as a Coupled Human and Natural System to represent the biophysical and immaterial elements, processes and interrelations. Further, the concepts of risk, UGI and ecosystem services come together in a risk system showing the compound hazards, the exposure, and the cascading vulnerabilities of the UGI. The drought and heat risk assessment framework distinguishes two stages, multi-risk analysis, and multi-criteria risk evaluation. The analysis includes definition and interpretation of the UGI situation under drought and heat conditions, analyzing the hazards, exposure, and vulnerabilities of the system, and translating the risk system into an indicator-based information system. Hereby, the vulnerability analysis of the biophysical UGI aspects comprises the susceptibility and resilience of UGI entities, as well as the degree to which providing ecosystem functions and services can be affected. The multi-criteria risk evaluation covers the assignment of thresholds and weights for indicators, in addition to the aggregation methods. The resulting framework intends to support local actors in the risk assessment of current and future conditions, fostering evidence-based decisions and interventions to deal with risks.

Plain Language Summary

The present study proposes a framework for jointly assessing the risks of drought and heat for urban green infrastructure (UGI) and their ecosystem services (ES). The study follows a systematic procedure to help understand the situation and to develop the framework, which compromises of two stages, analysis, and evaluation. The resulting framework aims to assist local actors in assessing present and future risks and identifying intervention alternatives for risk reduction.

1. Introduction

1.1. Background

According to the IPCC AR6, climate change is expected to increase the frequency, intensity, and the concurrence of drought and heat events in many urban areas across the globe in addition to uneven warming levels (IPCC, 2021a). For instance, a study by Guerreiro et al. (2018) showed that southern European cities will experience more drought events, whereas the duration of heat waves is expected to increase in most European cities according to the climate change low-impact scenario. Having more than 56% of the world's population, urban areas are particularly vulnerable to drought and heat hazards (Romero Lankao & Qin, 2011). The exothermic activities from certain industries and transportation modes, in addition to the built environment, trigger the heat island effect within cities (e.g., Peng et al., 2012; Liang & Keener, 2015). This threatens the health and livelihood of urban dwellers particularly during the period of heat waves (e.g., Zhao et al., 2014; Manoli et al., 2019). At the same time, the widely spread impermeable surfaces alter the urban water flows increasing the runoff and reducing groundwater recharge, making the urban areas more vulnerable to drought hazards (X. Zhang et al., 2019).

To address the climate-related increase of hydro-meteorological hazards, policymakers and practitioners are progressively planning and implementing urban green infrastructure (UGI) (I. C. Mell, 2017), considering that UGI are major building blocks for urban sustainability through social, economic, and environmental functions (Breuste et al., 2015). Indeed, their services can range from improving the human health (e.g., Coutts & Hahn, 2015), to conserving and enhancing urban biodiversity (e.g., Filazzola et al., 2019), and reducing GHG emissions (e.g., Fletcher et al., 2021). Even during extreme times such as the COVID-19 pandemic, green and blue spaces within the UGI were found beneficial to mental health of urban dwellers (e.g., Pouso et al., 2021). Moreover, the regulatory functions of UGI can tame natural hazards such as floods and droughts by facilitating infiltration and groundwater recharge (e.g., Gill et al., 2007; Zhang et al., 2012), as well as heat hazards through the cooling effect (e.g., Gillner et al., 2015; Ghosh and Das, 2018). Conversely, the different components of UGI are prone to drought and heat hazards and their functions under these hazards can be affected (e.g., Brune, 2016; Allen et al., 2021). Therefore, preserving the ecosystem services (ES) of UGI contributes to more resilient and sustainable urban areas as explained in Section 2.1.

Studies have demonstrated that the spatial and temporal overlap between drought and heat events can lead to more severe consequences (e.g., Shukla et al., 2014; Dong et al., 2018). Hence, analyzing them as interrelated issues and from a multi-risk perspective is needed to avoid misjudgment and underestimation. Having indicated the significance of UGI and its vulnerability to drought and heat, it is necessary to study and understand its drought and heat risks accounting for the direct risks on the UGI elements as well as the secondary risks for the ES provided by the UGI.

1.2. State of the art

Researchers have addressed the impacts resulting from drought and heat hazards on vegetation and water bodies on multiple spatial scales and in various contexts, and following different approaches. Droughts and heat events were examined as individual hazards affecting the physiology of the urban green and blue spaces (e.g., Juntakut, 2020; Kabano et al., 2021), their health (e.g., Bhuiyan et al., 2017), and their cooling functions (e.g., Allen et al., 2021). Considering the larger spatial scale, many studies looked into regional forest and water ecosystems under compound drought and heat conditions to assess the physiological impacts at regional or global levels (e.g., Allen et al., 2010; Zhang et al., 2016; Duan et al., 2017).

Some scholars adopted the ES concept while studying the drought and heat hazards. Raheem et al. (2019) conducted interviews to assess which ES are potentially vulnerable to droughts at a basin level. Whereas Kabisch et al. (2021) proposed a framework for assessing the regulating and recreational ES of urban parks under drought and heat conditions. A broader approach by Shah et al. (2020) addressed the topic by first highlighting the lack of adequate hazard-related risk assessments in the contexts of nature-based solutions (NBS), and subsequently proposed a risk assessment framework for socio-ecological systems (SES) with the aim of maximizing the effectiveness of NBS in disaster risk reduction. Other studies looked into management practices such as irrigating urban green spaces to sustain their cooling function under drought and heat conditions (Kool, 2021).

The prominent focus within the reviewed studies are the impacts of drought or heat events on the UGI. Nonetheless, it is noticeable that the literature addressing this topic lacks a holistic view on the risk processes involved, incorporating the vulnerability and resilience of the UGI and their ES to the compound drought and heat hazards. The study by Shah et al. (2020) comes close to address this gap, but has a broader perspective on the spatial dimension, the hazards, and exposed elements. It focuses on the implementation of NBS, and does neither consider the interdependencies between drought and heat hazards explicitly nor the risks for ES. Although the concept of risk assessment for drought and heat hazards is applied for different sectors such as agriculture (Nam et al., 2012), water supply (Jinno, 2010), and public health (Revich, 2011), it is yet to be adopted for UGI and their ES. Additionally, due to the interrelation of the two hazards from one side, and the reciprocity of the interrelation between the hazards and UGI from the other, considering the multi-risks and a systems approach are justified but also missing from literature.

1.3. Aim and Approach for Developing the Assessment Framework

The described research gap, in addition to the growing risks from drought and heat events, calls for further research in this field to understand the UGI situation under drought and heat conditions, and provide information on the occurring risks, which could be valuable for decision makers to reduce these risks. Accordingly, the aim of the study is to build knowledge on the drought and heat risks for UGI, indicating the interconnections and risk processes between the hazards, UGI and their ES. This is achieved by developing a drought and heat risk assessment framework for the UGI and their ES, to support judgement on the current and future risks and to set the course for effective decision making on potential risk-reduction alternatives.

A conceptual framework could carry different objectives from one study to the other, but is mainly based on concepts and theories that complement one another and together, help describe a phenomena or situation (Jabareen, 2009), whereas a methodological framework tends to provide guidance to the user through a structured set of methodical steps (McMeekin et al., 2020). The objective of the framework in the present research is to enable the assessment of drought and heat risks for UGI as part of the broader scope of risk management, and therefore, will include both conceptual and methodological tiers and referred to as the Drought and Heat Risk (DHR) Assessment Framework. Other authors have also developed conceptual frameworks in the field of risk assessment and climate adaptation (e.g., Begum et al., 2014; Shah et al., 2020). Developing assessment frameworks requires a combination of information from the literature, in addition to further analysis to form new constructs and knowledge. To achieve that, the study follows systematic steps of the development process inspired by Jabareen (2009) and Müller et al. (2020). Jabareen (2009) presents seven phases to generate a conceptual framework: phases 1 and 2 focus on mapping and understanding the data related to the phenomena, phases 3 to 6 focus on identifying, defining, interconnecting and synthesizing concepts, whereas phases 7 and 8 come after the framework is developed and include validation and continuous adaptation making it a dynamic process. On the other hand, Müller et al. (2020) summarize the approach into three phases: (i) defining and interpreting the considered subject, (ii) identifying and describing the main concepts, and (iii) constructing the framework.

The present study adapts the aforementioned three phases for developing a framework to fit the research goals with the intention of formulating the DHR Assessment Framework. The proposed main steps can be related to phases 1 to 6 from Jabareen's study, but leave behind phases 7 and 8 for further scientific research to test the framework and revisit it for continuous development. These steps are explained in the following.

1.3.1. Defining the situation of UGI under drought and heat conditions

To understand a situation and determine how to address it, a prerequisite is to adopt a consistent definition and clear classification of the main components under investigation and their interrelations to avoid ambiguity. In this study, the main components under focus are the UGI and their ES, which carry significant societal values. To analyze the situation of the UGI under drought and heat conditions, we apply a systems approach to address the multifaceted processes and have a holistic perspective on the situation. The systems approach has been adopted by many researches in the field of risks and natural resources management (e.g., Schanze, 2006; Bosch et al., 2007; Mai et al., 2020), with the advantages of including connectedness, relationships and the broader context of situations (Nyam et al., 2020).

Looking deeper into the considered situation we discover both, natural (e.g., climatic conditions and vegetation) and human-related (e.g., local residents and decision makers) components. Therefore, a systems approach is required, which includes the reciprocal interrelations between the subsystems and within these subsystems, to understand the situation. Few researchers followed a socio-ecological system (SES) approach to represent a risk-related situation, but drifting from the initial purpose of the SES framework (e.g., Smit et al., 2016; Bolaños-Valencia et al., 2019). Originally, the SES was focused on the common-pool resource management situations and evolved into a broader concept, which can make its comparison and transdisciplinary communication challenging (McGinnis & Ostrom, 2014; Partelow, 2018).

From a different viewpoint, a Coupled Human and Natural System (CHANS) approach was introduced by Liu et al. (2007) and specifies that human and natural systems are tied by two-way (reciprocal) interrelations represented by the flow of material, energy, and information (Liu et al., 2021). The CHANS framework can be applied to multi-spatial, -temporal, and -organizational levels and is easily communicated along disciplines and stakeholders (Alberti et al., 2011). Researchers applied the CHANS approach in multiple fields such as urban ecology (Alberti, 2008), flood protection (O'Connell & O'Donnell, 2014), climate services (Li et al., 2017), and risk and sustainability assessment (Müller et al., 2020). Given the features of the CHANS and its operational prospects, we have found it to be a suitable approach to understand the situation of the UGI with its ES under drought and heat conditions. While the CHANS will be represented in a simplified graphics showing the biophysical and immaterial aspects and flows, the biophysical aspects will be addressed in more details within Section 2.3. There, the propagation of drought and heat effects from the sources to the receptors are described.

1.3.2. Conceptualizing the risk system and translation into an information system

Building upon the CHANS and the conceptualization of a biophysical system, we address the drought and heat threats from a risk perspective and integrate the biophysical system as a risk system. To assess the risks from such events, analysis of the hazards, exposure, and vulnerability, in addition to the evaluation of these risks is needed (UNDRR, n.d.). Hence, we investigate the main concepts related to the drought and heat risk assessment procedure for UGI and their ES, as well as linking the process to the decision-making and broader risk management. Therefore, a non-systematic literature review and qualitative analysis are conducted to define and interrelate the following concepts: (1) urban drought and heat hazards; (2) vulnerability of UGI and ES; (3) risk system; (4) information system; (5) (multi-)risk assessment and its processes; (6) decision making and risk management.

1.3.3. Synthesizing the concepts and constructing the framework

The features and procedures of the different concepts are linked based on the logical flow of information and compiled together to establish the DHR Assessment Framework. This will be the focus of Section 4 where the hierarchical levels and sequences, and the graphical representation of the framework will be elaborated. The primary part of the framework, which is the risk assessment, is comprehensively presented based on the delineated risk system and linked to the other aspects of risk management such as the decision makers and risk reduction. The framework is supposed to set the conceptual and methodological ground for implementing a drought and heat risk assessment for UGI and their ES.

2. Defining the Situation of UGI under Drought and Heat Conditions

2.1. Conceptualization and Classification of UGI and ES

The concept of Urban Green Infrastructure (UGI) has evolved throughout the past decades and is a subsequent concept of earlier ideas such as parkways, green belts, garden cities, and greenways (I. Mell et al., 2017; Searns, 1995; Walmsley, 2006). Implementing UGI can simultaneously enhance biodiversity and human wellbeing contributing to transformations to more sustainable cities (Hansen et al., 2017; Rolf, 2020). UGI has been defined as the network of natural to semi-natural green (vegetation) and blue (water) features, where the infrastructure as whole offers a wide range of ecological and social benefits (Hansen et al., 2017). This study distinguishes between the concept of UGI and its biophysical components. The UGI concept stands out as a boundary entity connecting policymakers, planners, and the scientific community (Garmendia et al., 2016). On the other hand, the components of the UGI carry out biophysical functions that lead to services and benefits for the urban dwellers (Wang & Banzhaf, 2018). Although UGI can be considered under the umbrella of the NBS concept, it has stronger roots connecting it to the urban planning and development aspects (Kabisch et al., 2017).

Within the wide research on UGI, it was found that there is no consensus on the classification, which planners and practitioners can consistently adopt (Bartesaghi Koc et al., 2016; Young et al., 2014). Many studies focus on the biophysical aspects, structural types, and use of land in their classification (e.g., Anderson et al., 1976; Stewart & Oke, 2012; Lehmann et al., 2014). The current research paper aims to provide a framework for a spatial assessment of the risk as well as risks on the UGI, there functions and ES. Therefore, a spatial distinction in addition to the functional distinction are desirable characteristics for the classification of UGI. The spatial aspect is desirable to account for the commonly uneven distribution of drought and heat risks, whereas the functional distinction is necessary to relate to the vulnerability concept to the ecosystem services. Hence, the classification provided by the Biodiversity Information System for Europe (BISE), which focuses on the urban features of the green infrastructure, was found to fit our research specifications. UGI was categorized into seven types (BISE, n.d.): Building greens; urban green areas connected to grey infrastructure; parks and (semi)natural urban green areas (including urban forests); allotments and community gardens; agricultural land; green areas for water management; blue areas.

Ecosystem Services (ES) can be defined as the features of ecosystems which can be directly or indirectly utilized to improve human wellbeing (Fisher et al., 2009). The services are seen as an intermediate level between the biophysical functions of UGI and the nonmaterialistic benefits received by the human population, and contributing to the human wellbeing (Hansen & Pauleit, 2014; M. B. Potschin & Haines-Young, 2011). In our study, we differentiate services from functions by considering the latter as biophysical processes or properties with the purpose of supporting ecosystems and/or underpinning ecosystem services (Jax, 2016; Luck et al., 2009). Different classifications of ES appeared throughout the literature, but a standardized classification by the European Environmental Agency was created to have common accounting methods and potential comparisons (EEA, 2018). This classification proposes the division into 4 levels in an increasing order of specificity: sections (3), divisions (10), groups (24), and classes (66). The present study stresses the three main types of ES (sections) which are provisioning, regulation and maintenance, and cultural. Other studies include an additional type called "supporting services" (e.g., Egoh et al., 2012; Coutts & Hahn, 2015), and indicate that these services are fundamental to deliver the other services. However, we are confident that these can be considered as the biophysical functions that ecosystems such as UGI components can perform to deliver services as previously mentioned.

It is evident that different features of the UGI can deliver different ES (Hansen et al., 2017), but specific correlations are highly dependent on the contextual conditions. However, a report by Cvejić et al. (2015) included an inventory of elements of urban green spaces, which can be related to certain UGI elements, and linked to specific ES based on evidence from the literature. This demonstrated a great potential and diversity of ES provided by the UGI. Within the potential ES of the UGI, certain ES are relevant to drought and heat by reducing their risks (e.g., regulation of baseline flows and extreme events), whereof others are vulnerable to drought and heat (e.g., the nutrition, materials or energy from plants, surface water, and groundwater). The vulnerability of UGI's ES will be discussed further in Section 3.2.

2.2. Situation as Coupled Human and Natural System (CHANS)

This section of the study addresses the situation of the UGI under drought and heat conditions by interpreting the UGI as a CHANS, and showing the biophysical and immaterial interrelations. Figure 1 depicts how the main elements of the system are divided into human and natural subsystems in addition to the biophysical and immaterial interrelations.

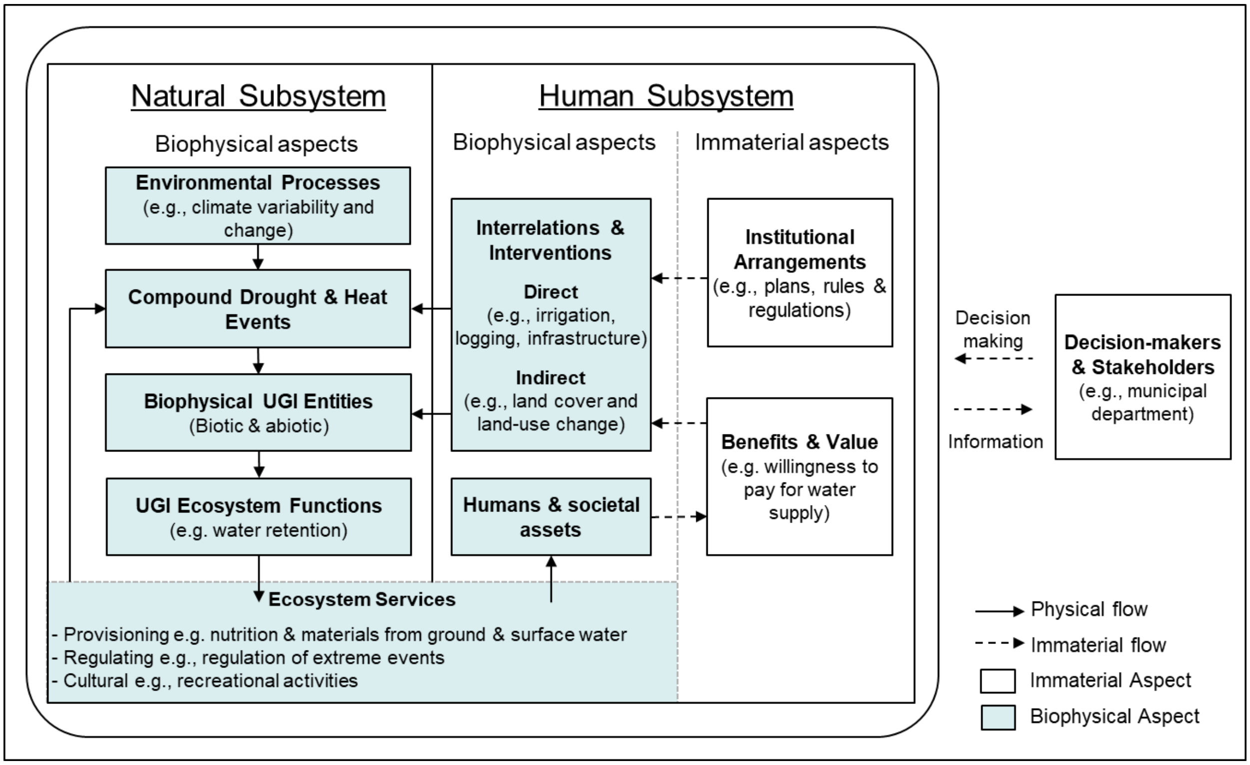

Figure 1. CHANS representation of the UGI under drought and heat conditions

On one side, the natural subsystem consists of the environmental processes causing drought and heat hazards affecting the UGI and receiving feedback, the biophysical elements of the UGI (e.g., vegetation), and UGI's ecosystem functions (e.g., water retention and storage). As mentioned in Section 2.1., the ES are in an intermediate position between the natural and human subsystems, but their characteristics are mostly biophysical rather than immaterial (e.g., nutrition, air purification, climate regulation, physical appearance). The ES are results of the UGI functions, and they are received by humans or societal assets through biophysical flows. In their turn, humans or societal assets create immaterial benefits and values out of the ES within the human subsystem. Additionally, the human subsystem consists of the institutional arrangements related to the compound drought and heat events and the UGI through direct and indirect interventions. Hence, the two subsystems are intra-connected through biophysical flows and immaterial interdependencies. Zooming out of the CHANS, the decision makers and stakeholders are involved in the situation through immaterial interdependencies by receiving information from the CHANS and making decisions concerning the system and possible interventions.

The effects of the drought and heat events on the natural and human subsystems, and can be translated into information for the immaterial aspects, especially for the assessment and decision making. Decision-making may respond to the hazards, protecting the UGI entities and reducing the impacts on the benefits and value from ES. The means of interference into the CHANS are shaped by institutional arrangements. The present study bounds its scope to the biophysical aspects of the CHANS from the environmental processes to the ES. In addition, it translates these aspects into an information system suitable for decision-making. A more detailed examination of the immaterial aspects remains to be done in further research.

2.3. Delineation and Description of the Biophysical System

To further understand the interdependencies within the system, the biophysical aspects of CHANS including human and natural components are investigated. Hereby, we dig deeper into how the drought and heat hazards propagate to affect the UGI and its ES. The propagation evolves over five stages as seen in Figure 2. The environmental processes either directly cause drought or heat events such as atmospheric conditions or act as indirect drivers in the case of urban and watershed conditions. Drought and heat hazards propagate to reach the UGI components though different pathways, and interact via certain processes such as evapotranspiration, soil moisture, and surface water runoff. The UGI entities can be classified into three main categories, biota (vegetation, animals, and micro-organisms), water bodies, and soils. An overarching combination of these entities form different ecosystem types. These UGI entities have various ecosystem functions, some of which are related to and affected by drought and heat events and presented in the fourth column of Figure 2. The functions reflect the UGI entities, in addition to the landscape functions where the UGI as spatial units can provide recreational or social functions. Alterations in the aforementioned functions can lead to effects on the UGI's ES from provisioning, regulating, and cultural dimensions. Additionally, direct effects from the drought and heat pathways to the UGI's ES can occur, whereas regulating feedback from the ES can help reduce extreme events such as urban droughts and heat. The community's interaction with the UGI is commenced at two levels, the interventions coming from decision makers, and from the people interacting with the UGI. Direct or indirect interventions may have various effects on UGI's components, and on the characteristics of drought and heat events.

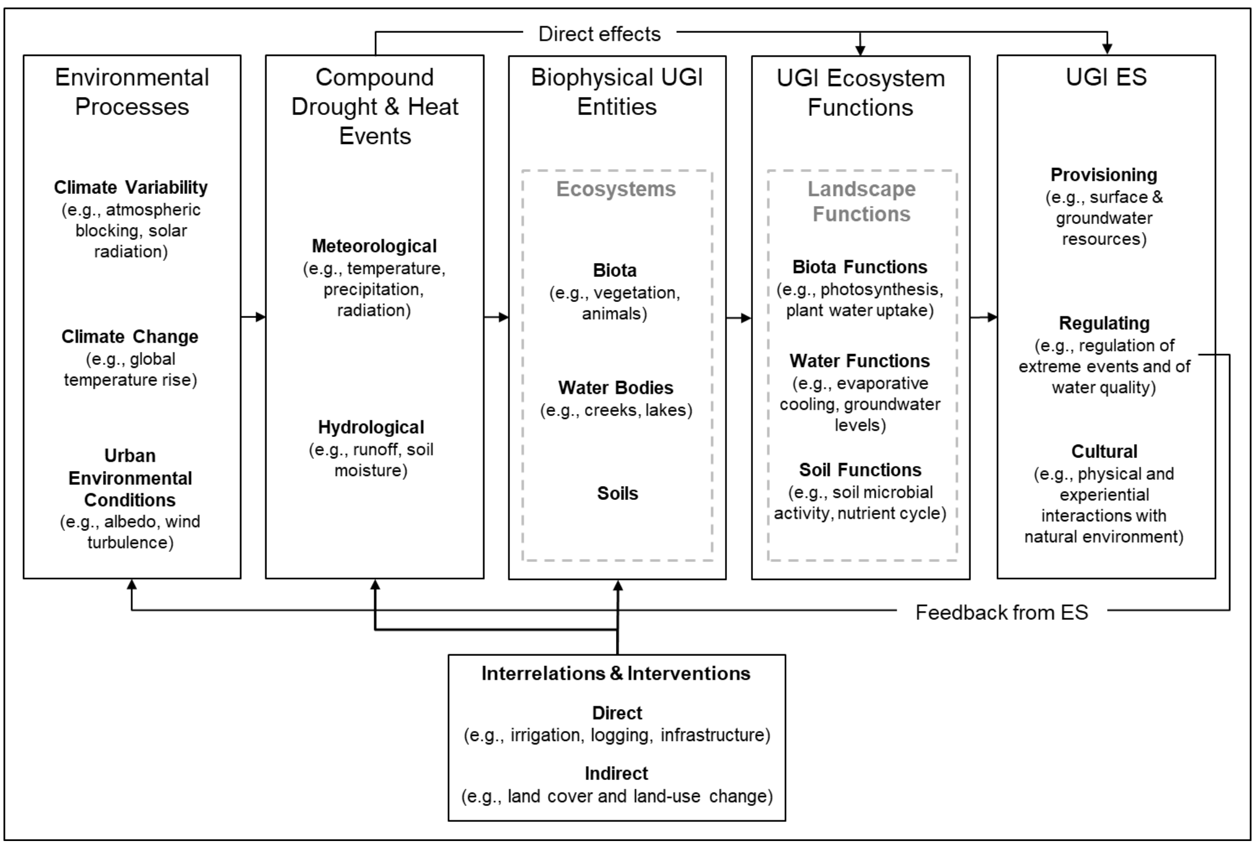

Figure 2. The biophysical system in relation to UGI

3. Conceptualizing the Risk System and Translation into an Information System

3.1. Urban drought and heat hazards

A drought hazard could be defines as the likelihood of an event to occur with temporary water shortage in different forms (meteorological, hydrological, agricultural, and socio-economic) compared to the long-term average (IPCC, 2021b; Wilhite, 2000). It can be characterized by severity, duration, probability of occurrence, and spatial distribution (Wilhite, 2000). The urban aspect of the drought hazard considered in this study is when the consequences of the drought reaches the urban area. This can occur directly, through reduced precipitation and/or high evapotranspiration rates within the urban spatial boarders, and indirectly, through reduced inflow of water from the basin to the urban area making it prone to the regional drought.

The other hazard considered is the heat hazard, which is likelihood of an event to occur where the maximum daily temperature exceeds the average maximum daily temperature by a certain degree for several days (e.g., WMO & WHO, 2015). It can also be characterized by severity, duration, probability of occurrence, and spatial distribution. In urban areas, this amplifies the urban effect of heat islands, where parts of urban areas retain higher temperatures than their surroundings (Leconte et al., 2015). This study incorporates both, heat waves and the urban heat island effect to reach the urban heat hazard.

It is worth mentioning that the main interrelationship between the drought and heat hazards is within the evapotranspiration process and through the related attributes such as temperature, wind, and solar radiation (Maes & Steppe, 2012). With the manifold attributes of both hazards, and their potential spatiotemporal concurrence, the UGI components react differently to each specific attribute or a combination of attributes. For example, certain plant species of the vegetation can be affected by long-term temperature increase (heat) with moderate severity whereas another species is vulnerable to short-term severe heat. Therefore, it is important to relate the hazards to the vulnerability attributes of the UGI and its ES.

3.2. Vulnerability of UGI and ES

This study introduced the UGI from an ecosystem services perspective with its contribution to human wellbeing and ultimately, the sustainability of urban areas (Section 2.1). However, the drought and heat hazards affect the biophysical processes and components of UGI and hinder them from delivering the expected ES (e.g., Juntakut, 2020; Kabano et al., 2021). One of the vulnerability concepts includes the susceptibility of biophysical entities and their coping capacity (equivalent to resilience), and the values or functions affected by the hazards (e.g., Blanco-Vogt & Schanze, 2014; Schanze, 2016). Hence, the vulnerability could be assessed over four tiers:

(1) The susceptibility and resilience of the UGI entities (constituting of biophysical structures).

(2) The degree to which ecosystem functions can be affected (constituting of biophysical processes)

(3) The degree to which ES can be affected (constituting of biophysical services)

(4) The degree to which human well-being can be affected (constituting of immaterial benefits and values)

It is essential to know that these tiers are not completely separate but rather interrelated, as the vulnerability of certain UGI entities can lead to vulnerability in delivering specific ES. Similar to the cascading services concept introduced by Haies-Young and Potschin (2010) between ecosystems and human wellbeing, the vulnerability is carried over from one aspect to the other starting from the exposed ecosystems of UGI reaching the benefits and values the community receives. Therefore, the vulnerability cannot be assessed in a straightforward manner, but rather requires deeper exploration and linking the hazards' attributes from one side, with the vulnerable UGI aspects, which according to the cascade concept, range from entities, functions, and ES to human well-being. Since the ES become of societal value when the community benefits from these services, the profile of the considered community and the institutional arrangements are the basis of the immaterial human well-being tier. Studying the vulnerability of this tier will be surpassing the scope of the study and can be referred to existing research (e.g., Berrouet et al., 2019) or further research to address. In summary, the present work considers the three vulnerability tiers based on the biophysical aspects of UGI entities, ecosystem functions, and ES.

To operationalize the vulnerability concept we ask the following question: What are the characteristics or properties that determine whether: (a) UGI survives during and recovers from drought and heat hazards, (b) the functions and ES will, and to what degree, be affected by the hazards? Being vulnerable to droughts and heat means that certain reduction of water availability (from precipitation, evapotranspiration, surface and subsurface flow), and/or increase in temperature compared to the average values, will lead to disturbances of the UGI component and hence reduced delivery of ES. Additionally, time and resources will be required for the effected UGI to return to partial or full functionality after the termination of the hazardous event. All this should be considered when analyzing the vulnerability tiers of the selected assessment endpoints from the biophysical system.

3.3. Risk System and Information System

"The potential for adverse consequences" is how the IPCC's 6th Assessment Report defines risk, and focusing that it should be directly linked to effects on human or ecological systems (IPCC, 2021b). From an operational definition, the risk is commonly considered a function of the hazard, exposure, and vulnerability (e.g., Blanco-Vogt & Schanze, 2014). Figure 3 in the lower part reflects on this definition and illustrates how different aspects of the cascading model between the UGI ecosystems towards human wellbeing are vulnerable within a simplified drought and heat risk system. Within the presented risk system the compound hazards propagate to the urban receptors reaching the exposed biophysical UGI, which are vulnerable on multiple levels (entities, functions, services, and human wellbeing).

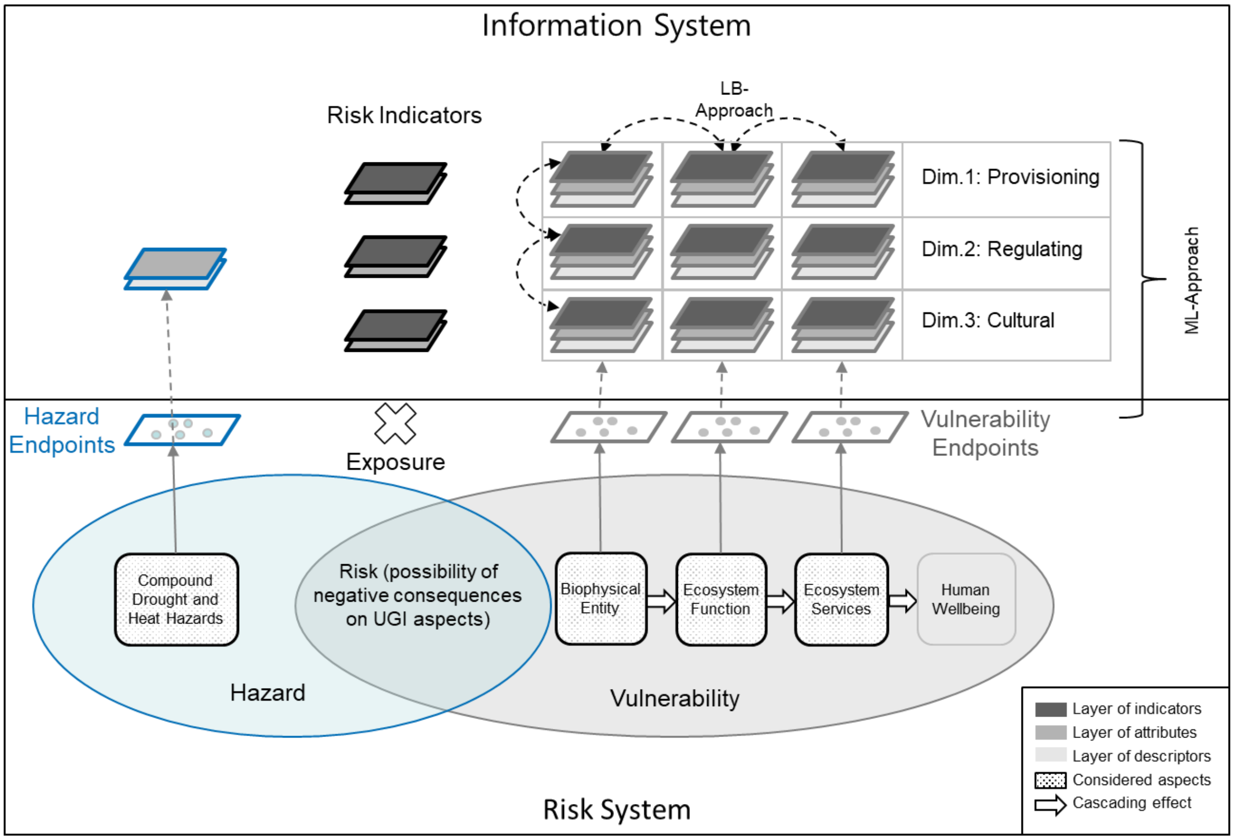

Figure 3. Risk System and its translation into the information system. The cascade model is based on Potschin and Haines-Young, (2011) and applying the Lane-based (LB) and Multi-layer (ML) approaches of Müller et al. (2021).

To study this risk system and provide decision support from the results, it is required to translate the biophysical aspects into information that describes the original situation epistemologically. The translated result is expressed here as information system. For the translation process, the elements of the risk system relevant for the assessment need to be selected. These system variables are named ‘endpoints’ and defined as entities of the system and their attributes, existing at different organizational levels, which can be used to interpret the state or performance of the system (Müller et al., 2020; Wolt et al., 2010). Endpoints identified for the assessment, are significant for the functioning of the system, and are also sensitive to disturbances such as drought and heat events (USEPA, 2003; Wolt et al., 2010). It is important to define these endpoints in order to set the boundaries or scope of the assessment framework and determine what information will be derived from the risk system. Müller et al. (2021) explain that these endpoints should be determined by researchers and/or practitioners using either a top-down approach (e.g., literature reviews) or bottom-up approach (e.g., participatory activities). Because of the multiple aspects of the risk system (hazard and vulnerability tiers), we will have endpoints representing these aspects, related to the compound drought and heat hazards, and the vulnerable UGI entities, functions and ES.

Müller et al. (2021) propose two approaches that can facilitate a translation from endpoints as biophysical layer to thematic indicators as information layers (multi-layer approach) and determine the intra- and interlinkages between the derived indicators (lane-based approach). With reference to the considered risk system, the information system spreads across hazards, exposure, vulnerability, and risk. The vulnerability information can be divided into multiple dimensions based on the nature of assessment. Within each dimension, layers of descriptors, attributes and indicators are identified based on the endpoints from the biophysical system. Descriptors are parameters that describe and characterize the vulnerability of UGI and ES with the advantage of providing a degree of flexibility in selecting available indicators based on the context of the area under consideration, making the framework more transferable. Attributes are qualities or parameters relevant to the proposed descriptors and are required for the calculation of indicators, whereas indicators require descriptors and attributes to be derived, and are considered as operationalized means informing about the condition or state of the system. The lane-based approach enables intra- and inter-connecting the indicators based on having common or related attributes. Linking indicators is significant for building the information system and inspecting how it represents the risk system. One of the advantages of the lane-based approach is identifying key indicators and dependencies, where a change in one key indicator might cause changes in other indicators. Figure 3 presents an overview of these two approaches within the information system.

Since the goal is to assess the risks for UGI and its ES, it is favorable to have the three ES types, provisional, regulatory, and cultural, as the three dimensions of the information system. Furthermore, we have explained that the vulnerability should be assessed at three tiers, which are the UGI entities, ecosystem functions, and ES. Hence, each dimension will spread over these tiers where vulnerability is represented. This allows the assessment of vulnerability and risks over a specific dimension (e.g., risks for provisional services), a complete tier (e.g., risks for UGI delivering ES), or combinations of the two. An example of translating a biophysical assessment endpoint into a descriptor and indicators is provided below.

a. Endpoint: Soil water regulation (filtering, retention and infiltration) (ecosystem function)

b. Descriptor: Sealed soil

c. Attributes: total area; sealed area, etc.

d. Possible indicator: Proportion of impervious surface

3.4. (Multi-)Risk Assessment and its Procedure

Risk assessment is a component of the planning phase of risk management and includes the aspects of risk analysis and risk evaluation (Müller et al., 2021; Schanze, 2009). It helps understanding and addressing hazards and their potential consequences, and is a significant public-policy tool to support decision-making, defining research needs, and enables the evaluation of different regulatory alternatives (National Research Council, 2009). From this definition, we understand the significance of risk assessment for successful risk management, which is a systematic and holistic process to analyze, evaluate, and reduce the risk (Schanze, 2006; UNDRR, n.d.).

Figure 4 displays the risk phenomena and their manifestation alongside the information system, while considering the connection to the actors and decision makers. Comparing the biophysical and the information flows, we identify similarities in the way risks propagate and the information flows, where both start from the hazards on one side and the UGI on the other. However, the information system requires additional steps to generate an information pool based on attributes and indicators. This implies that the information from the compound drought and heat hazards as well as the exposure information should be assigned with the vulnerability information to produce risk information. The information system continues beyond the risk information, where the information is analyzed and transferred to a multi-criteria evaluation to support decision makers.

The information generated from the analysis is the basis of the evaluation process, and therefore, should be tailored for the local biophysical conditions and stakeholders' needs. Moreover, society typically represented by local actors, should participate in setting the goals and criteria of the risk evaluation by setting targets or tolerable levels of risk reflecting on the societal needs and the conceptualized risk system (Müller et al., 2021). This can be accomplished by weighting indicators, assigning thresholds, and aggregation methods. Therefore, the judgement on the risks is not only based on the general goal of reducing risk and sustaining benefits for the UGI, but also on the interests and values of the respective communities.

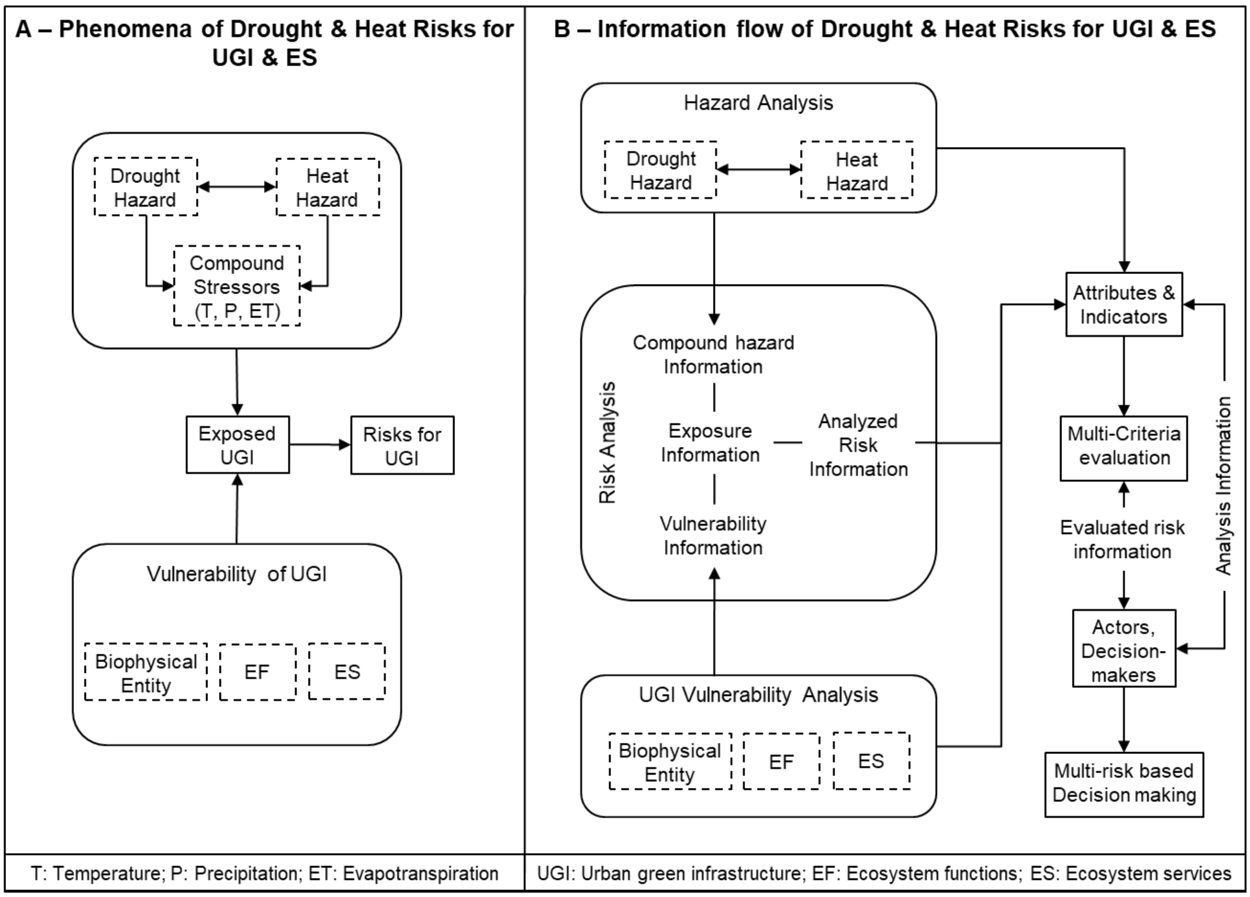

Figure 4. Risk phenomena and information: Comparing the biophysical processes and information flow

Another aspect to consider is whether to adopt a single risk, a multi-hazard, or a multi-risk approach to assess the drought and heat risks for UGI. Within a single risk approach, the risks resulting from each individual hazard are addressed separately (Komendantova et al., 2016). Whereas in the multi-hazard approach, the droughts and heat can be considered simultaneously enabling the interactions between these hazards, but this approach focuses on a single risk as an output only (Kappes et al., 2012). In contrast, the multi-risk approach enables the analysis of multiple risks from various hazards, and considering different vulnerabilities of the exposed elements such as economic, social, and environmental (Gallina et al., 2016). Due to the interrelated nature of drought and heat hazards, in addition to the multifaceted vulnerabilities of the UGI's ES, it is desirable to address the situation with a multi-risk approach. Several other hazards (e.g., storms, floods) are also relevant for UGI, and the proposed framework can be further expanded to accompany these hazards. However, it is fair to expect that broadening the multi-risk assessment exponentially increases the combinations of vulnerabilities to hazards and the resources required to assess the risks.

3.5. Decision making and risk management

According to the IPCC (2021b), risk management includes plans, actions, strategies or policies to diminish the adverse potential consequences from a probabilistic or magnitude perspective. For such risk-informed plans, actions, or strategies, risk assessments are considered as key inputs (Risk Assessment and Risk Management: Review of Recent Advances on Their Foundation, 2016). From a generic point of view, the classic theory behind decision-making states that decisions aim to increase benefits (gains) and reduce costs (losses), requiring framing and decomposition, and evaluation to achieve the decision (Edwards, 1954; Tversky & Kahneman, 1986). Another focus of decision-making is determining whether action(s) is needed in response to a specific situation, and selecting the most suitable action alternative(s) (Meempatta et al., 2019). Decision-making also plays a significant role within the risk management procedure, and one of the main purposes of risk assessments is to support decision-making, and help identify most suitable alternatives for selection (Lin et al., 2015). Within two of its guiding principles, the Sendai Framework for Disaster Risk Reduction 2015-2030 mentions that decision-making should be inclusive, risk-informed, and that local communities should be empowered to take decision-making responsibilities (UNDRR, 2015).

In decisions related to the UGI, many actors can be involved, and it highly depends on the share of responsibility within each regional context. For example, an environmental department within the municipality could be the main decision maker, whereas in another situation, civil society members (e.g., NGOs) may have the responsibility of managing and protecting certain UGI components, and reducing the risks whenever needed. In many cases, the decision makers are a group of stakeholders having defined or overlapping roles.

Furthermore, regularly reviewing decisions based upon updated risk information could be beneficial due to the ever changing background conditions (e.g., climate and land use) and the implementation of risk-reduction alternatives. Hence, Mochizuki et al. (2015) stress the importance of an iterative decision-making process for risk reduction as part of risk management, to enable continuous adaptation to new information. Part of the focus of the present study lies on the risk assessment aspect for supporting decision makers. However, decision-making within risk management also requires input on different aspects including defining the level of tolerable risk, uncertainties, feasibility of alternatives, and existing policies.

4. The DHR Framework

According to the definition of risk assessment, it includes the stages of risk analysis and risk evaluation. Both of these stages require input from the drought and heat risk system of the UGI and related ES such as meteorological and socio-economic data. The output information from risk assessment should be beneficial for decision makers to select risk reduction alternatives. The relations between the discussed concepts sets the general structure of the DHR framework composed of the risk system from one side, the decision makers from another, the risk assessment in between, and connected to the risk reduction stage external to the framework. Moreover, we include both, the conceptual and methodological perspectives within both stages of the risk assessment, providing a systematic conceptualization and operationalization of the drought and heat situation for UGI with their ES.

The definition and interpretation of the situation as a CHANS, defining the risk system, and identifying assessment endpoints fall into the conceptual aspect of risk analysis. The risk system is analyzed by identifying and interrelating system elements, and defining the vulnerability and risk aspects to be assessed. As mean of analysis of the drought and heat situation with its hazards, exposure and vulnerability, the multi-layer approach is used to translate the biophysical endpoints into information layers representing the ES dimensions of provisioning, regulating, and cultural services. This information provided in layers of descriptors, attributes and indicators is intra- and inter-linked through a lane-based approach. In their turn, the analyzed risk information act as inputs for the risk evaluation which includes setting the criteria of the evaluation, and comparing the calculated risk with the tolerable level of risk. This stage is accompanied by methodological steps of assigning indicators with thresholds and weights, selecting the aggregation method to evaluate the risks, and calculating the vulnerability and risk indicators. The different methods of Multi-attribute Decision Making (MADM) are known to be helpful in supporting decision-makers in the selection between a finite number of alternatives according to multiple (conflicting) criteria (Rao, 2007). Therefore, MADM methods are beneficial for the drought and heat risk assessment for UGI.

Benefiting from the MADM, the outputs of the risk assessment can act as guidance for the stakeholders to set or edit the risk management plans and strategies. The engagement of stakeholders in risk management comes with several benefits such as better understanding of the risk situation, building trust, and sharing responsibility of actions (Ndlela, 2019). These benefits occur at both stages of the risk assessment, at the analysis and the evaluation phases. Engagement is not only through receiving information about the assessed elements, but also by sharing the knowledge and experiences on the system and the process of evaluating it, as well as judgement on the best alternatives considering the risks and other relevant aspects. Following that step, the selection and implementation of alternatives can occur as part of risk reduction. The DHR assessment framework is presented in Figure 5.

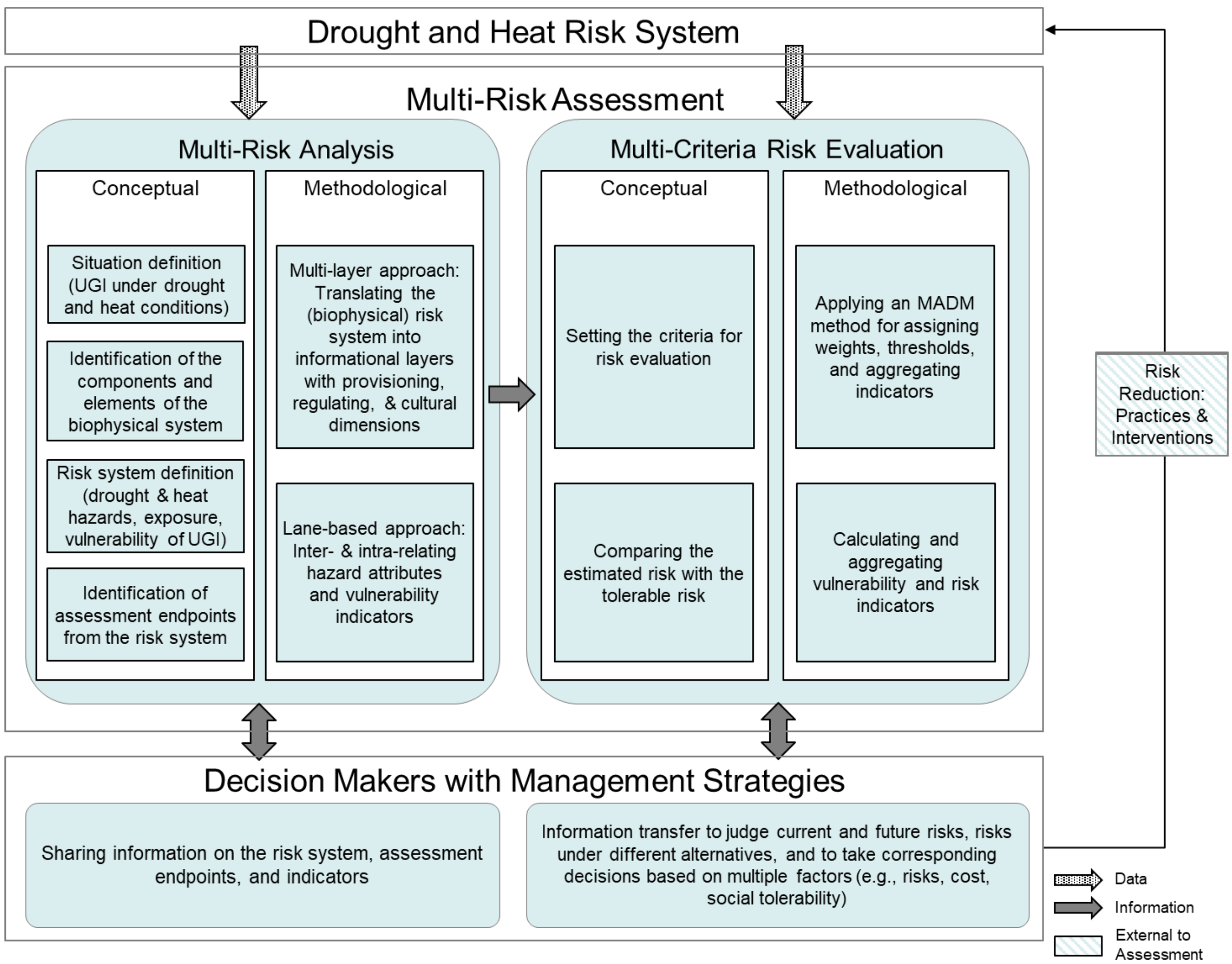

Figure 5. The DHR assessment framework

5. Discussion

Compared to other studies addressing the drought and heat related challenges for UGI or similar urban ecological components (e.g., Juntakut, 2020; Kabano et al., 2021), the DHR assessment framework introduces a risk assessment perspective to further understand the situation and uses multi-criteria evaluation to support decision-making. An added value of following a risk approach to address the situation, was the ability to deduce endpoints from different components of the risk system (compound hazards and three tiers of vulnerability) compared to the impact assessment that focus on the receptors. Additionally, the DHR risk assessments allows the consideration of different timespans to account for possible future changes (e.g., risks under different alternatives).

In contrast to comparable conceptual frameworks (e.g. Shah et al. 2020), or methodological frameworks (e.g., Kabisch et al. 2021), the development of the DHR framework underwent a systematic conceptualization of the situation and provided methodological aspects to assess the drought and heat risks for UGI. A well-defined procedure was followed by defining the situation (problem) as a CHANS, conceptualizing the risk and information systems, and bringing concepts together to construct the framework. Despite that the SES approach (e.g., Shah et al. 2020) could capture the social and ecological dimensions, and that the system dynamics approach (e.g., Zarghami & Dumrak, 2021) provides causal relationships and predicts system behavior, the CHANS approach was suitable to represent the material and immaterial aspects of the system as well as the reciprocal interrelations represented by biophysical and information flows.

The framework is built on three major concepts with strong foundations. These are the concepts of multi-risk assessment, urban green infrastructure, and ecosystem services. The multi-risk assessment interrelates two hazards, and extends beyond the UGI entities to include the vulnerability tiers of ecosystem functions and ES. Additionally, the dimensions of ES (provisional, regulating, and cultural) are reflected in the risk assessment. This is a novel conceptualization within the state of the art, especially that most of the literature's focus is on implementing the UGI concepts for climate adaptation (e.g., Gill et al., 2007).

During the development phase, we also came upon potential limitations in the scope of the framework. Firstly, the focus of this study was on the biophysical aspects of the CHANS and does not include the immaterial aspects relevant for the translation into the information system such as institutional arrangements and socio-economic benefits the community receives, although the considered community benefiting from the UGI can be itself vulnerable from droughts and heat. Considering the vulnerability of ES, partially addresses the socio-economic vulnerability, since it is connected through the cascading effects. Moreover, the DHR assessment framework intends to be generic in terms of the contextual application, and the degree of transferability needs to be tested. For example, testing whether the framework could account for data scarce regions, or different climatic zones where the biota behaves differently and provides diverse ES. Another characteristic to consider is how the information output from the risk assessment provides support for the risk reduction stage, which could be an extension to the framework. It should be stressed that the decision-making process on selecting alternatives for risk reduction in general also requires judgement on aspects beyond risk such as other values and interests of stakeholders such as economic feasibility and social acceptance.

Finally, the transdisciplinary characteristics of the framework should be highlighted. As the CHANS representation (Fig. 1) shows, the situation includes hazards, UGI ecosystems, and their wide range of services, which can impact the health, water and food security, and the biodiversity of urban areas. In addition, the human interventions play direct and indirect roles in altering the biophysical system. This implies that the empirical application of the DHR assessment framework will require knowledge from and ideally, involvement of multiple scientific fields (e.g., environmental risks, urban ecology) and non-scientific expertise. The selection of experts and the nature of their involvement highly depends on the type of UGI considered. Further, the framework could be adapted or expanded to additional hazards or vulnerability aspects in urban contexts.

6. Conclusions and Outlook

The present study develops a risk assessment framework on conceptual and methodological aspects by following a systematic procedure for its development. The situation of UGI under drought and heat conditions is interpreted as a coupled human and natural system after the system elements have been identified. This provides a simplified overview on how the elements of the system are interconnected to external natural and human interventions, and differentiates between the biophysical and immaterial aspects of the situation. Furthermore, we analyzed the biophysical aspects of the system and the propagation of the drought and heat events to reach the UGI and its ES. Afterwards, the risk system was conceptualized, enabling the identification of assessment endpoints and paving the way for the construction of the DHR assessment framework for UGI.

The framework links the risk assessment with the drought and heat risk system as well as with the decision makers, and provides them supporting information for effective decision-making in the broader context of risk management.

The current research provides two main outcomes, understanding the situation and interpreting it as a risk system, and a framework providing conceptual and methodological means to generate risk knowledge, which helps manage UGI and their ES under compound drought and heat conditions. This framework includes approaches, such as the systems approach (e.g., CHANS), and accompanies it with indicator based methods (e.g., multi-layer). Other methods, e.g., modeling, could have been suggested to address the situation instead of indicator based methods, but this depends on whether the goal is to represent the holistic system (i.e. using indicators) or a more specific receptor(s). Therefore, the framework can be either adopted fully, including the suggested methods, or only with the conceptual aspects.

Although researchers can directly benefit from the proposed conceptual and methodological framework, further operationalization can make this framework also viable for local actors to use and perform a drought and heat risk assessment for their UGI. To achieve that objective, an indicator-based tool needs to be developed through further research, and the framework should be tested in different contextual conditions making it simple, flexible, and with minimum complications for scientists and local actors to use.

Author Contribution

Raghid Shehayeb: Literature review, conceptualization, analysis, visualization, writing - original draft. Regine Ortlepp: Conceptualization, supervision, writing - review & editing. Jochen Schanze: Conceptualization, supervision, writing - review & editing.

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Open Research

The authors declaire that no additional data was used other than the mentioned references.

References

Alberti, M. (2008). *Advances in Urban Ecology*. Springer US. https://doi.org/10.1007/978-0-387-75510-6

Alberti, M., Asbjornsen, H., Baker, L. A., Brozovic, N., Drinkwater, L. E., Drzyzga, S. A., Jantz, C. A., Fragoso, J., Holland, D. S., Kohler, T. (Tim) A., Liu, J. (Jack), McConnell, W. J., Maschner, H. D. G., Millington, J. D. A., Monticino, M., Podestá, G., Pontius, R. G., Redman, C. L., Reo, N. J., … Urquhart, G. (2011). Research on Coupled Human and Natural Systems (CHANS): Approach, Challenges, and Strategies. *Bulletin of the Ecological Society of America*, *92*(2), 218–228. https://doi.org/10.1890/0012-9623-92.2.218

Allen, C. D., Macalady, A. K., Chenchouni, H., Bachelet, D., & Mcdowell, N. (2010). A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. *Forest Ecology and Management*, *259*(4), 660–684. https://doi.org/10.1016/j.foreco.2009.09.001ï

Allen, M. A., Roberts, D. A., & McFadden, J. P. (2021). Reduced urban green cover and daytime cooling capacity during the 2012–2016 California drought. *Urban Climate*, *36*. https://doi.org/10.1016/j.uclim.2020.100768

Anderson, J. R., Hardy, E. E., Roach, J. T., & Witmer, R. E. (1976). *A land use and land cover classification system for use with remote sensor data* (Vol. 964). Geological Survey Professional Paper. https://books.google.de/books?hl=en&lr=&id=dE-ToP4UpSIC&oi=fnd&pg=PA1&ots=sYll-Y5d4E&sig=GsDLzZjDb7m2pbtgzIJvaf9nzwI&redir_esc=y#v=onepage&q&f=false

Risk assessment and risk management: Review of recent advances on their foundation, 253 European Journal of Operational Research 1 (2016). https://doi.org/10.1016/j.ejor.2015.12.023

Bartesaghi Koc, C., Osmond, P., & Peters, A. (2016). Towards a comprehensive green infrastructure typology: a systematic review of approaches, methods and typologies. *Urban Ecosystems 2016 20:1*, *20*(1), 15–35. https://doi.org/10.1007/S11252-016-0578-5

Begum, R. A., Sarkar, M. S. K., Jaafar, A. H., & Pereira, J. J. (2014). Toward conceptual frameworks for linking disaster risk reduction and climate change adaptation. *International Journal of Disaster Risk Reduction*, *10*(PA), 362–373. https://doi.org/10.1016/J.IJDRR.2014.10.011

Berrouet, L., Villegas-Palacio, C., & Botero, V. (2019). A social vulnerability index to changes in ecosystem services provision at local scale: A methodological approach. *Environmental Science & Policy*, *93*, 158–171. https://doi.org/10.1016/J.ENVSCI.2018.12.011

Bhuiyan, C., Saha, A. K., Bandyopadhyay, N., & Kogan, F. N. (2017). Analyzing the impact of thermal stress on vegetation health and agricultural drought–a case study from Gujarat, India. *GIScience and Remote Sensing*, *54*(5), 678–699. https://doi.org/10.1080/15481603.2017.1309737

BISE. (n.d.). *Typology of green infrastructure*. Retrieved October 27, 2021, from https://biodiversity.europa.eu/green-infrastructure/typology-of-gi

Blanco-Vogt, A., & Schanze, J. (2014). Assessment of the physical flood susceptibility of buildings on a large scale - Conceptual and methodological frameworks. *Natural Hazards and Earth System Sciences*, *14*(8), 2105–2117. https://doi.org/10.5194/nhess-14-2105-2014

Bolaños-Valencia, I., Villegas-Palacio, C., López-Gómez, C. P., Berrouet, L., & Ruiz, A. (2019). Social perception of risk in socio-ecological systems. A qualitative and quantitative analysis. *Ecosystem Services*, *38*, 100942. https://doi.org/10.1016/J.ECOSER.2019.100942

Bosch, O. J. H., King, C. A., Herbohn, J. L., Russell, I. W., & Smith, C. S. (2007). Getting the big picture in natural resource management-systems thinking as 'method' for scientists, policy makers and other stakeholders. *Systems Research and Behavioral Science*, *24*(2), 217–232. https://doi.org/10.1002/sres.818

Breuste, J., Artmann, M., Li, J., & Xie, M. (2015). Special Issue on Green Infrastructure for Urban Sustainability. *Journal of Urban Planning and Development*, *141*(3). https://doi.org/10.1061/(asce)up.1943-5444.0000291

Brune, M. (2016). *Urban trees under climate change Potential impacts of dry spells and heat waves in three German regions in the 2050s*. www.climate-service-center.de.

Coutts, C., & Hahn, M. (2015). Green Infrastructure, Ecosystem Services, and Human Health. *International Journal of Environmental Research and Public Health 2015, Vol. 12, Pages 9768-9798*, *12*(8), 9768–9798. https://doi.org/10.3390/IJERPH120809768

Cvejić, R., Eler, K., Pintar, M., Železnikar, Š., Haase, D., Kabisch, N., & Strohbach, M. (2015). *A typology of urban green spaces, ecosystem services provisioning services and demands* (V10 ed., Vol. 7). Green Surge Project D3.1. https://ign.ku.dk/english/green-surge/rapporter/D3.1_A_typology_of_urban_green_spaces.pdf

Dong, L., Mitra, C., Greer, S., & Burt, E. (2018). The dynamical linkage of atmospheric blocking to drought, heatwave and urban heat island in southeastern US: A multi-scale case study. *Atmosphere*, *9*(1), 33. https://doi.org/10.3390/ATMOS9010033

Duan, H., Wu, J., Huang, G., Zhou, S., Liu, W., Liao, Y., Yang, X., Xiao, Z., & Fan, H. (2017). Individual and interactive effects of drought and heat on leaf physiology of seedlings in an economically important crop. *AoB PLANTS*, *9*(1). https://doi.org/10.1093/AOBPLA/PLW090

Edwards, W. (1954). The theory of decision making. *Psychological Bulletin*, *51*(4), 380–417. https://doi.org/10.1037/H0053870

EEA. (2018). *CICES 5.1*. https://cices.eu/

Egoh, B., Drakou, E. G., Dunbar, M. B., Maes, J., & Willemen, L. (2012). Indicators for mapping ecosystem services: a review. In *JRC Scientific and Policy Reports* (Issue Report EUR 25456 EN). https://doi.org/10.2788/41823

Filazzola, A., Shrestha, N., & MacIvor, J. S. (2019). The contribution of constructed green infrastructure to urban biodiversity: A synthesis and meta-analysis. In *Journal of Applied Ecology* (Vol. 56, Issue 9, pp. 2131–2143). John Wiley & Sons, Ltd. https://doi.org/10.1111/1365-2664.13475

Fisher, B., Turner, R. K., & Morling, P. (2009). Defining and classifying ecosystem services for decision making. *Ecological Economics*, *68*(3), 643–653. https://doi.org/10.1016/J.ECOLECON.2008.09.014

Fletcher, D. H., Likongwe, P. J., Chiotha, S., Nduwayezu, G., Mallick, D., Uddin Md., N., Rahman, A., Golovatina, P., Lotero, L., Bricker, S., Tsirizeni, M., Fitch, A., Panagi, M., Ruiz Villena, C., Arnhardt, C., Vande Hey, J., Gornall, R., & Jones, L. (2021). Using demand mapping to assess the benefits of urban green and blue space in cities from four continents. *Science of The Total Environment*, 147238. https://doi.org/10.1016/j.scitotenv.2021.147238

Gallina, V., Torresan, S., Critto, A., Sperotto, A., Glade, T., & Marcomini, A. (2016). A review of multi-risk methodologies for natural hazards: Consequences and challenges for a climate change impact assessment. *Journal of Environmental Management*, *168*, 123–132. https://doi.org/10.1016/J.JENVMAN.2015.11.011

Garmendia, E., Apostolopoulou, E., Adams, W. M., & Bormpoudakis, D. (2016). Biodiversity and Green Infrastructure in Europe: Boundary object or ecological trap? *Land Use Policy*, *56*, 315–319. https://doi.org/10.1016/J.LANDUSEPOL.2016.04.003

Ghosh, S., & Das, A. (2018). Modelling urban cooling island impact of green space and water bodies on surface urban heat island in a continuously developing urban area. *Modeling Earth Systems and Environment*, *4*(2), 501–515. https://doi.org/10.1007/s40808-018-0456-7

Gill, S. E., Handley, J. F., Ennos, A. R., & Pauleit, S. (2007). Adapting cities for climate change: The role of the green infrastructure. *Built Environment*, *33*(1), 115–133. https://doi.org/10.2148/benv.33.1.115

Gillner, S., Vogt, J., Tharang, A., Dettmann, S., & Roloff, A. (2015). Role of street trees in mitigating effects of heat and drought at highly sealed urban sites. *Landscape and Urban Planning*, *143*, 33–42. https://doi.org/10.1016/j.landurbplan.2015.06.005

Guerreiro, S. B., Dawson, R. J., Kilsby, C., Lewis, E., & Ford, A. (2018). Future heat-waves, droughts and floods in 571 European cities. *Environmental Research Letters*, *13*(3). https://doi.org/10.1088/1748-9326/aaaad3

Haines-Young, R., & Potschin, M. (2010). The links between biodiversity, ecosystem services and human well-being. In D. G. Raffaelli & C. L. J. Frid (Eds.), *Ecosystem Ecology* (Vol. 1, pp. 110–139). Cambridge University Press. https://doi.org/10.1017/CBO9780511750458.007

Hansen, R., & Pauleit, S. (2014). From multifunctionality to multiple ecosystem services? A conceptual framework for multifunctionality in green infrastructure planning for Urban Areas. *Ambio*, *43*(4), 516–529. https://doi.org/10.1007/S13280-014-0510-2

Hansen, R., Rolf, W., Pauleit, S., Born, D., Bartz, R., Kowarik, I., Lindschulte, K., & Becker, C. (2017). *Urban Green Infrastructure. A foundation of attractive and sustainable cities. Pointers for municipal practice*. Federal Agency for Nature Conservation (BfN). https://doi.org/10.13140/RG.2.2.22593.45925

IPCC. (2021a). Annex VII: Glossary. In J. B. R. Matthews, J. S. Fuglestvedt, V. Masson-Delmotte, V. Möller, C. Méndez, D. R. Van, A. Reisinger, & S. Semenov (Eds.), *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press. In Press. https://doi.org/https://dx.doi.org/10.1017/9781009157896.022

IPCC. (2021b). Summary for Policymakers. In V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, & B. Zhou (Eds.), *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press. In Press. https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_SPM.pdf

Jabareen, Y. (2009). Building a Conceptual Framework: Philosophy, Definitions, and Procedure.

International Journal of Qualitative Methods, *8*(4), 49–62. https://doi.org/10.1177/160940690900800406

Jax, K. (2016). Ecosystem functions: a critical perspective. In M. Potschin, R. Haines-Young, R. Fish, & R. K. Turner (Eds.), *Routledge Handbook of Ecosystem Services* (pp. 42–44). Routledge.

Jinno, K. (2010). Risk Assessment of a Water Supply System during Drought. *Http://Dx.Doi.Org/10.1080/07900629550042399*, *11*(2), 185–204. https://doi.org/10.1080/07900629550042399

Juntakut, P. (2020). Assessment of Drought Impacts on Urban Green Areas with the Climatic Drought Index in Nakhonratchasima City, Thailand. *CRMA Journal*, *1*, 15–22. https://ph01.tci-thaijo.org/index.php/crma-journal/article/view/243153

Kabano, P., Lindley, S., & Harris, A. (2021). Evidence of urban heat island impacts on the vegetation growing season length in a tropical city. *Landscape and Urban Planning*, *206*, 103989. https://doi.org/10.1016/j.landurbplan.2020.103989

Kabisch, N., Kraemer, R., Brenck, M. E., Haase, D., Lausch, A., Luttkus, M. L., Mueller, T., Remmler, P., Döhren, P. von, Voigtländer, J., & Bumberger, J. (2021). A methodological framework for the assessment of regulating and recreational ecosystem services in urban parks under heat and drought conditions. *Https://Doi.Org/10.1080/26395916.2021.1958062*, *17*(1), 464–475. https://doi.org/10.1080/26395916.2021.1958062

Kabisch, Nadja, Korn, H., Stadler, J., & Bonn, A. (2017). *Nature-Based Solutions to Climate Change Adaptation in Urban Areas—Linkages Between Science, Policy and Practice*. Springer Nature. https://doi.org/10.1007/978-3-319-56091-5_1

Kappes, M. S., Keiler, M., von Elverfeldt, K., & Glade, T. (2012). Challenges of analyzing multi-hazard risk: a review. *Natural Hazards 2012 64:2*, *64*(2), 1925–1958. https://doi.org/10.1007/S11069-012-0294-2

Komendantova, N., Scolobig, A., Garcia-Aristizabal, A., Monfort, D., & Fleming, K. (2016). Multi-risk approach and urban resilience. *International Journal of Disaster Resilience in the Built Environment*, *7*(2), 114–132. https://doi.org/10.1108/IJDRBE-03-2015-0013

Kool, T. (2021). *Linking cooling by nature and urban drought reduction to irrigation measures: Tackling the urban heat island and droughts simultaneously* [TU Delft]. https://repository.tudelft.nl/islandora/object/uuid%3Ac04486a5-126a-45d8-85b3-edb5f3cf8856

Leconte, F., Bouyer, J., Claverie, R., & Pétrissans, M. (2015). Using Local Climate Zone scheme for UHI assessment: Evaluation of the method using mobile measurements. *Building and Environment*, *83*, 39–49. https://doi.org/10.1016/J.BUILDENV.2014.05.005

Lehmann, I., Mathey, J., Rößler, S., Bräuer, A., & Goldberg, V. (2014). Urban vegetation structure types as a methodological approach for identifying ecosystem services - Application to the analysis of micro-climatic effects. *Ecological Indicators*, *42*, 58–72. https://doi.org/10.1016/j.ecolind.2014.02.036

Li, Y., Giuliani, M., & Castelletti, A. (2017). A coupled human-natural system to assess the operational value of weather and climate services for agriculture. *Hydrology and Earth*

System Sciences, *21*(9), 4693–4709. https://doi.org/10.5194/HESS-21-4693-2017

Liang, M. S., & Keener, T. C. (2015). Atmospheric Feedback of Urban Boundary Layer with Implications for Climate Adaptation. *Environmental Science and Technology*, *49*(17), 10598–10606. https://doi.org/10.1021/acs.est.5b02444

Lin, L., Nilsson, A., Sjölin, J., Abrahamsson, M., & Tehler, H. (2015). On the perceived usefulness of risk descriptions for decision-making in disaster risk management. *Reliability Engineering & System Safety*, *142*, 48–55. https://doi.org/10.1016/J.RESS.2015.04.012

Liu, J., Dietz, T., Carpenter, S. R., Alberti, M., Folke, C., Moran, E., Pell, A. N., Deadman, P., Kratz, T., Lubchenco, J., Ostrom, E., Ouyang, Z., Provencher, W., Redman, C. L., Schneider, S. H., & Taylor, W. W. (2007). Complexity of coupled human and natural systems. *Science*, *317*(5844), 1513–1516. https://doi.org/10.1126/science.1144004

Liu, J., Dietz, T., Carpenter, S. R., Taylor, W. W., Alberti, M., Deadman, P., Redman, C., Pell, A., Folke, C., Ouyang, Z., & Lubchenco, J. (2021). Coupled human and natural systems: The evolution and applications of an integrated framework: This article belongs to Ambio's 50th Anniversary Collection. Theme: Anthropocene. *Ambio*, *50*(10), 1778–1783. https://doi.org/10.1007/s13280-020-01488-5

Luck, G. W., Harrington, R., Harrison, P. A., Kremen, C., Berry, P. M., Bugter, R., Dawson, T. R., De Bello, F., Diaz, S., Feld, C. K., Haslett, J. R., Hering, D., Kontogianni, A., Lavorel, S., Rounsevell, M., Samways, M. J., Sandin, L., Settele, J., Sykes, M. T., … Zobel, M. (2009). Quantifying the Contribution of Organisms to the Provision of Ecosystem Services. *BioScience*, *59*(3), 223–235. https://doi.org/10.1525/BIO.2009.59.3.7

Maes, W. H., & Steppe, K. (2012). Estimating evapotranspiration and drought stress with ground-based thermal remote sensing in agriculture: a review. *Journal of Experimental Botany*, *63*(13), 4671–4712. https://doi.org/10.1093/JXB/ERS165

Mai, T., Mushtaq, S., Reardon-Smith, K., Webb, P., Stone, R., Kath, J., & An-Vo, D. A. (2020). Defining flood risk management strategies: A systems approach. *International Journal of Disaster Risk Reduction*, *47*, 101550. https://doi.org/10.1016/j.ijdrr.2020.101550

Manoli, G., Fatichi, S., Schläpfer, M., Yu, K., Crowther, T. W., Meili, N., Burlando, P., Katul, G. G., & Bou-Zeid, E. (2019). Magnitude of urban heat islands largely explained by climate and population. *Nature*, *573*(7772), 55–60. https://doi.org/10.1038/s41586-019-1512-9

McGinnis, M., & Ostrom, E. (2014). Social-ecological system framework: initial changes and continuing challenges. *Ecology and Society, Published Online: May 20, 2014 | Doi:10.5751/ES-06387-190230*, *19*(2). https://doi.org/10.5751/ES-06387-190230

McMeekin, N., Wu, O., Germeni, E., & Briggs, A. (2020). How methodological frameworks are being developed: Evidence from a scoping review. *BMC Medical Research Methodology*, *20*(1), 1–9. https://doi.org/10.1186/S12874-020-01061-4/FIGURES/3

Meempatta, L., Webb, A. J., Horne, A. C., Keogh, L. A., Loch, A., & Stewardson, M. J. (2019). Reviewing the decision-making behavior of irrigators. *WIREs Water*, *6*(5). https://doi.org/10.1002/WAT2.1366

Mell, I., Allin, S., Reimer, M., & Wilker, J. (2017). Strategic green infrastructure planning in Germany and the UK: a transnational evaluation of the evolution of urban greening policy and practice. *Http://Dx.Doi.Org/10.1080/13563475.2017.1291334*, *22*(4), 333–349. https://doi.org/10.1080/13563475.2017.1291334

Mell, I. C. (2017). Green infrastructure: reflections on past, present and future praxis. *Https://Doi.Org/10.1080/01426397.2016.1250875*, *42*(2), 135–145. https://doi.org/10.1080/01426397.2016.1250875

Mochizuki, J., Vitoontus, S., Wickramarachchi, B., Hochrainer-Stigler, S., Williges, K., Mechler, R., & Sovann, R. (2015). Operationalizing iterative risk management under limited information: Fiscal and economic risks due to natural disasters in Cambodia. *International Journal of Disaster Risk Science*, *6*(4), 321–334. https://doi.org/10.1007/S13753-015-0069-Y/FIGURES/5

Müller, A. B., Avellán, T., & Schanze, J. (2020). Risk and sustainability assessment framework for decision support in "water scarcity – water reuse" situations. *Journal of Hydrology*, *591*, 125424. https://doi.org/10.1016/J.JHYDROL.2020.125424

Müller, A. B., Avellán, T., & Schanze, J. (2021). Translating the 'water scarcity – water reuse' situation into an information system for decision-making. *Sustainability Science 2021*, 1–17. https://doi.org/10.1007/S11625-021-01077-9

Nam, W.-H., Choi, J.-Y., Yoo, S.-H., & Jang, M.-W. (2012). A decision support system for agricultural drought management using risk assessment. *Paddy and Water Environment 2012 10:3*, *10*(3), 197–207. https://doi.org/10.1007/S10333-012-0329-Z

National Research Council. (2009). Science and decisions: Advancing risk assessment. In *Science and Decisions: Advancing Risk Assessment*. The National Academies Press. https://doi.org/10.17226/12209

Ndlela, M. N. (2019). A Stakeholder Approach to Risk Management. In *Crisis Communication* (pp. 53–75). Palgrave Pivot, Cham. https://doi.org/10.1007/978-3-319-97256-5_4

Nyam, Y. S., Kotir, J. H., Jordaan, A. J., Ogundeji, A. A., Adetoro, A. A., & Orimoloye, I. R. (2020). Towards Understanding and Sustaining Natural Resource Systems through the Systems Perspective: A Systematic Evaluation. *Sustainability*, *12*(23), 9871. https://doi.org/10.3390/su12239871

O'Connell, P. E., & O'Donnell, G. (2014). Towards modelling flood protection investment as a coupled human and natural system. *Hydrology and Earth System Sciences*, *18*(1), 155–171. https://doi.org/10.5194/HESS-18-155-2014

Partelow, S. (2018). A review of the social-ecological systems framework. *Ecology and Society*, *23*(4). https://www.jstor.org/stable/26796887

Peng, S., Piao, S., Ciais, P., Friedlingstein, P., Ottle, C., Bréon, F. M., Nan, H., Zhou, L., & Myneni, R. B. (2012). Surface urban heat island across 419 global big cities. *Environmental Science and Technology*, *46*(2), 696–703. https://doi.org/10.1021/es2030438

Potschin, M. B., & Haines-Young, R. H. (2011). Ecosystem services: Exploring a geographical perspective. *Http://Dx.Doi.Org/10.1177/0309133311423172*, *35*(5), 575–594. https://doi.org/10.1177/0309133311423172

Pouso, S., Borja, Á., Fleming, L. E., Gómez-Baggethun, E., White, M. P., & Uyarra, M. C. (2021). Contact with blue-green spaces during the COVID-19 pandemic lockdown beneficial for mental health. *Science of The Total Environment*, *756*, 143984. https://doi.org/10.1016/J.SCITOTENV.2020.143984

Raheem, N., Cravens, A. E., Cross, M. S., Crausbay, S., Ramirez, A., Mcevoy, J., Zoanni, | Dionne, Deborah, |, Bathke, J., Hayes, M., Carter, S., Rubenstein, M., Schwend, A., Hall, K., & Suberu, P. (2019). Planning for ecological drought: Integrating ecosystem services and vulnerability assessment. *Wiley Interdisciplinary Reviews: Water*, *6*(4), e1352. https://doi.org/10.1002/WAT2.1352

Rao, V. (2007). Introduction to Multiple Attribute Decision-making (MADM) Methods. In *Decision Making in the Manufacturing Environment* (pp. 27–41). Springer London. https://doi.org/10.1007/978-1-84628-819-7_3

Revich, B. A. (2011). Heat as a risk factor for public health. *PULMONOLOGIYA*, *0*(4), 34–37. https://doi.org/10.18093/0869-0189-2011-0-4-34-37

Rolf, W. (2020). *Peri-urban farmland included in green infrastructure strategies promotes transformation pathways towards sustainable urban development* [Universität Potsdam]. https://doi.org/10.25932/PUBLISHUP-47700

Romero Lankao, P., & Qin, H. (2011). Conceptualizing urban vulnerability to global climate and environmental change. *Current Opinion in Environmental Sustainability*, *3*(3), 142–149. https://doi.org/10.1016/J.COSUST.2010.12.016

Schanze, J. (2009). Flood risk management – basic understanding and integrated methodologies . In *Methodologies for Integrated Flood Risk Management RESEARCH ADVANCES AT EUROPEAN PILOT SITES*. FLOODsite. http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.894.4806&rep=rep1&type=pdf#page=10

Schanze, J. (2006). Flood Risk Management - A Basic Framework. In J. Schanze, E. Zeman, & J. Marsalek (Eds.), *Flood Risk Management: Hazards, Vulnerability and Mitigation Measures* (pp. 1–20). Springer Netherlands.

Schanze, J. (2016). Resilience in flood risk management – Exploring its added value for science and practice. *E3S Web of Conferences*, *7*, 08003. https://doi.org/10.1051/e3sconf/20160708003

Searns, R. M. (1995). The evolution of greenways as an adaptive urban landscape form. *Landscape and Urban Planning*, *33*(1–3), 65–80. https://doi.org/10.1016/0169-2046(94)02014-7

Shah, M. A. R., Renaud, F. G., Anderson, C. C., Wild, A., Domeneghetti, A., Polderman, A., Votsis, A., Pulvirenti, B., Basu, B., Thomson, C., Panga, D., Pouta, E., Toth, E., Pilla, F., Sahani, J., Ommer, J., El Zohbi, J., Munro, K., Stefanopoulou, M., … Zixuan, W. (2020). A review of hydro-meteorological hazard, vulnerability, and risk assessment frameworks and indicators in the context of nature-based solutions. *International Journal of Disaster Risk Reduction*, *50*, 101728. https://doi.org/10.1016/j.ijdrr.2020.101728

Shukla, S., Mcnally, A., Husak, G., & Funk, C. (2014). A seasonal agricultural drought forecast system for food-insecure regions of East Africa. *Hydrol. Earth Syst. Sci*, *18*, 3907–3921. https://doi.org/10.5194/hess-18-3907-2014

Smit, N. J., Vlok, W., Van Vuren, J., Du Preez, L., Van Eeden, E., O'brien, G. C., & Wepener, V.

(2016). Socio-ecological System Management of the Lower Phongolo River and Floodplain Using Relative Risk Methodology Report to the Water Research Commission. In *Water Research Commission*. Water Research Commission. www.wrc.org.za

Stewart, I. D., & Oke, T. R. (2012). Local Climate Zones for Urban Temperature Studies. *Bulletin of the American Meteorological Society*, *93*(12), 1879–1900. https://doi.org/10.1175/BAMS-D-11-00019.1

Tversky, A., & Kahneman, D. (1986). Rational Choice and the Framing of Decisions. *The Journal of Business*, *59*(4), S251–S278. http://www.jstor.org/stable/2352759

UNDRR. (n.d.). *Terminology: Sendai Framework Terminology on Disaster Risk Reduction*. Retrieved May 9, 2022, from https://www.undrr.org/terminology

UNDRR. (2015). Sendai Framework for Disaster Risk Reduction 2015 - 2030. In *United Nations Office for Disaster Risk Reduction*. https://www.preventionweb.net/publication/sendai-framework-disaster-risk-reduction-2015-2030

USEPA. (2003). Generic Ecological Assessment Endpoints (GEAEs) for Ecological Risk Assessment. In *EPA/630/P-02/004F*. Risk Assessment Forum. https://www.epa.gov/risk/generic-ecological-assessment-endpoints-geae-ecological-risk-assessment

Walmsley, A. (2006). Greenways: multiplying and diversifying in the 21st century. *Landscape and Urban Planning*, *76*(1–4), 252–290. https://doi.org/10.1016/J.LANDURBPLAN.2004.09.036

Wang, J., & Banzhaf, E. (2018). Towards a better understanding of Green Infrastructure: A critical review. *Ecological Indicators*, *85*, 758–772. https://doi.org/10.1016/J.ECOLIND.2017.09.018

Wilhite, D. A. (2000). Drought as a Natural Hazard: Concepts and Definitions. In D. A. Wilhite (Ed.), *Drought: A Global Assessment* (Vol. 1, pp. 3–18). Routledge. http://digitalcommons.unl.edu/droughtfacpubhttp://digitalcommons.unl.edu/droughtfacpub/69

Wolt, J. D., Keese, P., Raybould, A., Fitzpatrick, J. W., Burachik, M., Gray, A., Olin, S. S., Schiemann, J., Sears, M., & Wu, F. (2010). Problem formulation in the environmental risk assessment for genetically modified plants. *Transgenic Research*, *19*(3), 425–436. https://doi.org/10.1007/s11248-009-9321-9

World Meteorological Organization (WMO), & World Health Organization (WHO). (2015). *Heatwaves and Health: Guidance on Warning-System Development* (G. McGregor, P. Bessemoulin, K. Ebi, & B. Menne (eds.)). World Meteorological Organization (WMO). https://www.who.int/globalchange/publications/WMO_WHO_Heat_Health_Guidance_2015.pdf

Young, R., Zanders, J., Lieberknecht, K., & Fassman-Beck, E. (2014). A comprehensive typology for mainstreaming urban green infrastructure. *Journal of Hydrology*, *519*(PC), 2571–2583. https://doi.org/10.1016/J.JHYDROL.2014.05.048

Zarghami, S. A., & Dumrak, J. (2021). A system dynamics model for social vulnerability to natural disasters: Disaster risk assessment of an Australian city. *International Journal of Disaster*

Risk Reduction, *60*, 102258. https://doi.org/10.1016/J.IJDRR.2021.102258

Zhang, B., Xie, G., Zhang, C., & Zhang, J. (2012). The economic benefits of rainwater-runoff reduction by urban green spaces: A case study in Beijing, China. *Journal of Environmental Management*, *100*, 65–71. https://doi.org/10.1016/j.jenvman.2012.01.015

Zhang, X., Chen, N., Sheng, H., Ip, C., Yang, L., Chen, Y., Sang, Z., Tadesse, T., Lim, T. P. Y., Rajabifard, A., Bueti, C., Zeng, L., Wardlow, B., Wang, S., Tang, S., Xiong, Z., Li, D., & Niyogi, D. (2019). Urban drought challenge to 2030 sustainable development goals. In *Science of the Total Environment* (Vol. 693, p. 133536). Elsevier B.V. https://doi.org/10.1016/j.scitotenv.2019.07.342

Zhang, Y., Xiao, X., Zhou, S., Ciais, P., McCarthy, H., & Luo, Y. (2016). Canopy and physiological controls of GPP during drought and heat wave. *Geophysical Research Letters*, *43*(7), 3325–3333. https://doi.org/10.1002/2016GL068501

Zhao, L., Lee, X., Smith, R. B., & Oleson, K. (2014). Strong contributions of local background climate to urban heat islands. *Nature*, *511*(7508), 216–219. https://doi.org/10.1038/nature13462