FINAL DRAFT

ASSESSING SOCIO-HYDROLOGICAL RESILIENCE IN URBAN METROPOLITAN ENVIRONMENTS: A MEXICAN PERSPECTIVE

Clara Olóriz Sanjuán, Flor García Becerra, Mariana Villada Canela, José Alfredo Ramírez, Ismael Aguilar Benítez and Andrew Barkwith[1]

Abbreviated title: SOCIO-HYDROLOGICAL ASSESSMENT IN MEXICO

Abstract: Growing population and the increasing global trend of human migration from rural to urban environments are leading to an expansion of metropolitan landscapes, which threatens water security and hydrological environments within cities. Often water security and metropolitan hydrology are approached as two separate issues. Subsequently, social aspects of infrastructure inclusiveness and the social registers of hydrological landscapes are left behind. The disconnect between water management and society, and their resulting impacts, such as drought, flood or poor water quality, are exacerbated by climate change and demand the introduction of new water management strategies. We present the socio-hydrological resilience (SHR) concept as an interdisciplinary holistic vision, which integrates socio-ecological methodologies with resilient water management practices. We examine traditional practices and present three novel approaches to water management in Mexico. On this basis, we define a set of socio-hydrological indicators that may be used to assess the resilience of urban environments to future change. We propose qualitative SHR indicators based on water security, social and hydrological aspects. Finally, we propose a coupled method to evaluate the integration and interdependencies of these indicators. To gauge the potentially wide-ranging impacts of these alternative approaches and to assess future approaches, a quantitative set of multidisciplinary indicators is required. This is discussed but requires further research.

Keywords Socio-hydrological resilience; metropolitan; water security

[1] Clara Olóriz Sanjuán (Architectural Association School of Architecture Clara.Oloriz@aaschool.ac.uk), Flor García Becerra (Universidad Autónoma Metropolitana fgarcia@correo.cua.uam.mx), Mariana Villada Canela (Universidad Autónoma de Baja California mvilladac@uabc.edu.mx), José Alfredo Ramírez (Architectural Association School of Architecture alfredo@aaschool.ac.uk), Ismael Aguilar Benítez (El Colegio de la Frontera Norte iaguilar@colef.mx) and Andrew Barkwith (British Geological Survey andr3@bgs.ac.uk)

<u>Table of Contents</u> **<u>Page</u>**

1. Introduction and key terms

Growing population and the increasing global trend of human migration from rural to urban environments are leading to an expansion of metropolitan landscapes, which threatens water security and hydrological environments within cities. Often water security and metropolitan hydrology are approached as two separate issues. Subsequently, social aspects of infrastructure inclusiveness and the social registers of hydrological landscapes are left behind. The disconnect between water management and society, and their resulting impacts, such as drought, flood or poor water quality, are exacerbated by climate change and demand the introduction of new water management strategies. Using case studies from around Mexico we examine traditional practices and novel approaches to water management and define a set of socio-hydrological indicators that may be used to assess the resilience of urban environments to future change.

In this chapter we give a brief outline of widely used key terms such as water security, climate change, metropolitan design and socio-hydrological resilience as these definitions underpin both traditional and innovative water management practices. We provide a brief review of existing practices in Mexico, highlighting the limitations of traditional water management approaches and how they often disregard social aspects and ignore the wider hydrological systems in which they sit. To address these limitations, we present the *socio-hydrological resilience* (SHR) concept as an interdisciplinary holistic vision, which integrates socio-ecological methodologies with resilient water management practices. Novel approaches towards water management are presented at three scales: metropolitan (10^1 km), urban (10^0 km) and architectural (10^{-1} km). These approaches are discussed retrospectively within the proposed SHR interdisciplinary framework. To gauge the potential impacts of these alternative approaches and to assess those of future approaches, a quantitative set of multidisciplinary indicators is required. We propose a set of qualitative SHR indicators based on water security, social and hydrological aspects related to the novel initiatives described in study cases. Finally, we propose a method to evaluate the integration and interdependencies of these aspects. Refining these indicators and their weighting is discussed, but ultimately left open for future research where they could be further developed into quantitative indicators and weighting formulas for evaluation of water management proposals.

1.1. SECURITY, CLIMATE CHANGE AND METROPOLITAN DESIGN

In relation to water management, socio-hydrological resilience standards can be built on the notion of water security, which is severely threatened by a changing climate and rapid urbanization of the metropolitan environment and its surrounding rural regions. Here we provide a brief definition of these terms in order to frame the discussion for this chapter.

The 'dynamic and constantly evolving dimensions of water and water-related issues' has led to various definitions of water security over the past decade (Grey & Sadoff, 2007; Houdret, Kramer, & Carius, 2010; UNESCO-IHP, 2012). The United Nations (UN) and UNESCO use a working-definition to describe water security and provide an outlook for addressing current and perceived future water challenges (UN, 2013; UNESCO-IHP, 2012). Under the UN and UNESCO definition, water security is 'the capacity of a population to safeguard sustainable access to adequate quantities of acceptable quality water for sustaining livelihoods, human well-being, and socio-economic development, for ensuring protection against water-borne pollution and water-related disasters, and for preserving ecosystems in a climate of peace and political stability' (UNESCO-IHP, 2012). A holistic, interdisciplinary approach to sustainable water management is required to achieve water security. It is imperative that any approach contributes not only to social-economic development, but also 'reinforces societal resilience to environmental impacts and water-borne diseases without compromising the present or future health of populations and ecosystems' (UN, 2013). The concept of water security and its attainment is applicable to multiple scales: from individual, household and community through urban and metropolitan to national and international. Water availability plays a key role in the water security concept and is affected by changes in climate, population and land-use.

Water availability, quality and disasters are conditioned by climate change. A warming climate will likely lead to greater evaporation and precipitation at the global scale, with a highly uneven distribution of precipitation. Runoff is expected to increase in high latitudes and decrease in mid-latitudes and subtropical regions (Arnell, 1999). Episodes of flood and drought are forecast to be greater in frequency and intensity, which will undoubtedly increase stress on water resources and security. 'Climate change over the 21st Century is projected to reduce renewable surface water and groundwater resources in most dry subtropical regions, intensifying competition for water amongst sectors' (IPCC, 2014). Global climate changes may be intensified by the concentration of urbanized zones in metropolitan areas via microclimate changes. Microclimate changes are caused by local variations in population (urban, peri-urban and rural), land use (percent area of pasture, crops, urban land, etc.), and land cover (percent area of trees and bare earth) (Ellis & Ramankutty, 2008). For example, urban heat islands result from the modification of land cover, where reduced vegetation cover, increased impervious cover and complex cityscape surfaces lead to lowered evaporative cooling, augmented heat storage and sensible heat flux (Patz, Campbell-Lendrum, Holloway, & Foley, 2005). Compiling these local changes can lead to appreciable impacts at the regional scale. Beyond exacerbating global climate change, microclimate changes such as the urban heat island effect can exert the greatest impact on local climatic conditions. 'Dark surfaces, such as asphalt roads or rooftops, can reach temperatures 30-40 °C higher than the surrounding air.' Consequently, most cities have shown to be 5 to 11 °C warmer than their surrounding rural areas (Aniello, Morgan, Busbey, & Newland, 1995; Frumkin, 2002).

Human-induced local or regional modifications to ecosystems range from considering humans merely agents of ecosystem transformation (ecosystem engineers) or a force rivaling climatic and geologic processes, able to irreversibly alter an ecosystem's form, process, and biodiversity. The latter relates to the urban environment, where human population can be dense enough that local resource consumption and waste production become a significant component of local biogeochemical cycles and other ecosystem processes (Ellis & Ramankutty, 2008). Rapid urbanization has exacerbated the impact that climate change poses to water security. Urban growth has amalgamated cities and towns into *agglomerations* with several urban areas and cores. Highly attractive for economic and industrial activities, as well as employment, these agglomerations are known as conurbations, city-regions, urban regions, metropolitan regions or global city-regions (Brenner & Schmid, 2011) depending on their configuration, size, scale or genesis. These agglomerations demand new sustainable approaches towards urban management that are, in many cases, not evolving at the same pace as population growth, especially in relation to water security. These new forms of management pose significant governance challenges leading to social inequality and affecting the way agglomerations are spatially configured, whilst requiring design strategies that offer alternatives.

Migration to rapid growth areas generates social and economic inequality, especially in the suburbs. 'Many peri-urban areas in developing regions are associated with poverty. The poor peri-urban resident may have moved-in and established residence in precarious conditions or may have resided in the area before the urban encroachment and so have a rural background. Poor, ex-rural residents living on the fringes of cities are considered to be very vulnerable since they are subjected to a livelihood transmutation while they try to escape poverty' (Méndez-Lemus & Vieyra, 2014). Legal and administrative delimitation of these conurbations is often complex. The merging of urban areas and towns is independent of their administrative boundaries, which results in fragmented management and a lack of systemic and integrated visions. Attempting to define the spatial impact of metropolitan resource requirements adds further complexity. To fuel rapid urbanization, resources are imported at national and global scales. In the case of water, resources are often extracted from remote sources and wastewater disposed of outside urban centers in a linear consumption-waste (take, make and dispose) model. The inability to define physical boundaries poses further administrative challenges, due to metropolitan impacts surpassing official limits. To overcome these two challenges, a paradigm shift in water management that includes circular, systemic and multiscale approaches is required. New approaches must be flexible enough to be incorporated within larger design strategies that can explore other modes of multi-scalar administrative delimitations, whilst maintaining the ability to address social inequality.

1.2. SOCIO-HYDROLOGICAL RESILIENCE (SHR)

To build a holistic, interdisciplinary approach that integrates social and hydrological aspects under rapid urbanization and climate change challenges, we explore the emerging notion of SHR. SHR departs from a more consolidated model of social resilience (SR), which is recognized as an interdisciplinary concept (from engineering, ecology, economics, psychology, sociology, urbanism and architecture), a multifaceted phenomenon (social, spatial, economic) and as an aspect to consider in recent decision-making and governance mechanisms, and implies a way of collaborative and transdisciplinary work.

SR is defined as 'the ability of groups or communities to avoid, cope with, learn, adapt and recover from external tensions and disturbances as a result of social, political and environmental change' (Adger, 2000; de Kraker, 2017; Saja, Teo, Goonetilleke, & Ziyath, 2018; Shaw, Scully, & Hart, 2014). SR has been approached from different system thinking perspectives that seek to include social aspects of resilience, based on a framework of sub-categories (social structure, social capital, social mechanisms, social equity, and social belief) (Saja et al., 2018). SR may also consider elements of 'social learning, social memory, mental models and knowledge-system integration, vision and 'scenario building, leadership, agents and actor groups, social networks, institutional and organizational inertia and change, adaptive capacity, transformability and adaptive governance' (Folke, 2006). Investigations have emphasized SR as a way to understand the effects and dynamics of the socio-ecological system on the human system, however, there is no defined method to measure it in a socio-hydrological context.

To assess linkages with water security, SR has been 'linked to a community's ability to access critical resources' (Langridge, Christian-Smith, & Lohse, n.d.); deal with disasters (droughts or floods) (Saja et al., 2018); cope with changes in water availability or quality (Wurl, Gámez, Ivanova, Imaz Lamadrid, & Hernández-Morales, 2018); or with sustainability (Milman & Short, 2008). Hence, managers, scientists and communities must decide between working with 'individual system processes or viewing the system from a more abstracted level' (Blair & Buytaert, 2016). In this sense, it is important to investigate concepts and indicators to measure urban processes involving the social and hydrological domains for the design of future metropolitan infrastructure and sustainable water management. Mao et al. (2017) proposed the SHR concept. SHR implies 'understanding and assessing resilience in coupled socio-hydrological contexts,' considering inter-connections between socio-hydrology and resilience. They also 'identify three existing framings of resilience for different types of human–water systems and subsystems […] (1) the water subsystem highlighting hydrological resilience to anthropogenic hazards; (2) the human subsystem, foregrounding social resilience to hydrological hazards; and (3) the coupled human–water system, which exhibits socio-hydrological resilience.' Using the SHR concept, Wurl et al. (2018) 'argue that the coupled human-water system is the most appropriate tool to design strategies for resilient management of hydrological resources.' Ciullo et al. (2017) use the SHR concept to integrate two different types of socio-hydrological systems in human–flood interactions and feedback mechanisms: green systems, whereby societies deal with risk via non-structural measures and technological systems, whereby risk is dealt with also by structural measures such as levees.

The SHR concept represents a potential for a transdisciplinary framework to assess local study cases in urban environments where water security and management, social resilience, micro and global climate change, and traditional and metropolitan design can be integrated and measured to create resilient models of urban space.

2. Existing practices in Mexico

2.1. REVIEW OF MEXICO'S WATER AVAILABILITY AND DEMAND

Since 2012, the Mexican Constitution established the access, disposal and sanitation of water as a human right. However, the provision of rights has had serious limitations throughout the nation. Mexico is a country under severe water stress. It has approximately 0.1% of the total freshwater globally available whilst being among the top 10 consumers of water in the world (197,425 million m^3/year), with principal users being: agriculture, 76%; general public, 15%; thermoelectric plants, 5%; and industry in general, 4%. Consumption rates are not uniform in time or space, for example, in Mexico City the Tlalpan borough has a water provision of less than 40 m^3/cap/year, whilst the Miguel Hidalgo borough has a consumption rate estimated at 190 m^3/cap/year. This difference in water use, demand and availability is characteristic of the country's water issues (PUEC UNAM, 2010; Rosalva Landa, 2014).

The availability of usable water is a complex problem that includes geographical distribution, pollution and overexploitation. Mexico has a significant percentage of its territory under desert and semi-arid climates, primarily in the central and northern parts of the country. In several areas of the center and north, water availability levels are currently lower than 2,500 m^3/cap/year. In the Baja California peninsula, Rio Grande region and northern basins it is estimated that water availability will be less than 1,000 m^3/cap/year by 2020, considered by the WMO as the minimum threshold to satisfy basic needs. At the same time, south-southeast Mexico, which has a more humid climate, has almost seven times more water than the rest of the country, with a water availability in excess of 23,000 m^3/cap/year in the south. Regional population and wealth exacerbate the impacts of non-uniform water distribution. Central and northern regions have 77% of the national population and generate 82% of the GDP, while they only have on average 33% of the water resource. Nationally, this places central Mexico (State of Mexico, Puebla, Tlaxcala, Morelos, Hidalgo and Mexico City) with the highest level of pressure on its water resources (CONAGUA, 2017; Rosalva Landa, 2014).

Water availability is further limited due to widespread contamination of natural water bodies with municipal and industrial wastewaters. Nationally, 42.5% (±11.5%) of municipal wastewater is treated, introducing an estimated 191.5 (±84) m^3/s of raw wastewater into nature. Also contributing to the degradation of water quality are informal effluents introduced in areas that lack centralized sanitation services. Nationally, 11% of the population lack these services, however, there are regions, such as the states of Oaxaca and Guerrero, where up to 30% of the population lacks formal sanitation. On the industrial side, 216 m^3/s of raw wastewater are emitted. Surface water contamination is causing epidemiological problems in communities living near the riverbeds in Central Mexico, such as the Atoyac, Santiago, Lerma, Tula and Coatzacoalcos rivers. The implications related to the lack of municipal and industrial wastewater treatment in Mexico are serious. In 2017 32% of all the tested water bodies had water quality issues, while in central Mexico 49% of sites were found to be contaminated (CONAGUA, 2017).

Water scarcity combined with the threat of pollution has led to the overexploitation of groundwater resources. In 1975 there were 32 aquifers defined as overexploited by CONAGUA (National water commission). This increased to 80 by 1985 and 106 in 2006. In contrast, the per capita availability of water in Mexico has decreased significantly since the middle of the last century: in 1950 it was 18,035 m^3/cap/year and in 2013 it was 3,982 m^3/cap/year, a rate determined as low by the United Nations Development Program (CONAGUA, 2017).

2.2. CONVENTIONAL TECHNOLOGIES AND THEIR LIMITATIONS IN MEXICO

2.2.1. Conventional technologies and centralized systems under stress

The nature of high-infrastructure water and sewage systems (forcemains, treatment plants, pumping stations, etc.) does not allow sufficient flexibility or resiliency to deal with the expected impacts of population and climate changes this century. Centralized urban water and wastewater systems consume large amounts of energy in their 'processing phases, including purification, distribution, and sewage treatment' (Cheng, 2002; Jothiprakash & Sathe, 2009). Due to the stress currently placed on energy systems, water and sanitation systems need to be redesigned in order to remain effective. Water purification and sanitation technologies have reached their technological limits to treat recalcitrant contaminants (pharmaceuticals, microplastics, pesticides, etc.) (Garcia-Becerra & Ortiz, 2018). Furthermore, high-infrastructure systems tend to require a close asset management approach. So far, centralized systems tend to lack stable financing across the globe (Panebianco & Pahl-Wostl, 2006). In Mexico, municipal water management has been decentralized, going from the federal to the state and then, to the municipal level. As a result, the majority of municipalities have foregone paying the operation and maintenance costs associated with sanitation services.

2.2.2. Linear urban water metabolism

Linear material flows of take-dispose are in direct conflict with our planet's cyclical system (Zaman, 2015). Usage of natural resources, including water, implies almost directly their disposal as waste and our current water consumption habits do not consider its direct reuse, for example, lost cost-saving opportunities from reusing greywater and runoff in agriculture and landscaping. As we move closer to the limits of urban ecosystems' carrying capacities, the need to manage water and wastewater in closed production cycles becomes critical. New water and sanitation systems should include diverse water reuse applications, less water-intensive urban and industrial designs and long-term sustainability concepts, such as circular economies and production schemes (Connett, 2013; Zaman, 2015). It is noteworthy that beyond solving critical environmental problems, cyclical sustainable water and sanitation approaches can be instrumental in achieving sustainable urbanism and activating their local economy (Lee, Pedersen, & Thomsen, 2014; Puppim De Oliveira et al., 2013).

In the usual framework of city growth, recovery of resources (particularly water resources) is not considered. To achieve sustainability, it is necessary to transform the linear approach to one that is circular-partially-closed, allowing water (and other resources) be recovered, reused and recycled (3R approach). A closed cycle in which waste and all wastewater is recycled is unrealistic, however, a partially closed cycle allows improved water management that incorporates wastewater. A circular approach prioritizes the restoration and regeneration of resources to maintain its greater usefulness and value, separating the overall development of the inefficient consumption of finite resources, based on the assumption of large amounts of easily accessible resources (Ellen MacArthur Foundation, 2015).

A clear indicator of the linear approach to urban water management in Mexico is the investment plan for the so-called strategic projects, which focus on Mexico City and traditional infrastructure. The Valley of Mexico (which contains the city of Mexico) concentrates 47% of the total investment in *strategic* projects. These projects are developed in the great cities of the urban system: Mexico City, Guadalajara, Monterrey, Leon, Guanajuato, San Luis Potosí; Acapulco, Ixtapa, Zihuatanejo; among others. Conventional infrastructure such as dams, aqueducts and sewage treatment plants absorb half of the budget. Long distance aqueducts that supply large cities are often employed in these projects: Cutzamala system, Stage IV (827 km); Tecolutla-Necaxa Aqueduct (131 km); third line of the Cutzamala system (77.6 km); Monterrey VI (372 km); the Chapultepec Aqueduct (33 km); are some examples. Projects to remove wastewater from large cities are also given priority under these projects. Despite a national program targeting the reuse of all wastewater (Objective 1.2.1.), neither maintenance or rehabilitation of water supply sources appear in these strategic projects.

The current situation of scarcity and greater uncertainty in future water resources demands a new perspective in which wastewater is seen as a potential potable resource with the added benefits of energy production and nutrient recovery. However, in Mexico, almost all water treated in the urban environment is discharged into the surrounding area, while sludge is usually disposed of in landfills.

2.3. URBAN GROWTH IN MEXICO

Worldwide, rapid population growth and urbanization are posing new water and sanitation engineering and infrastructure challenges. Water is key in metropolitan design and growth processes. As stated by Meinzen-Dick and Appasamy (2002), ‘of all the challenges posed by the dramatic growth of cities, none will continue to have a greater impact on the quality of human life or the environment than the provision of water, and the treatment of waterborne wastes’. Urban growth increases both water demand and impairment of water sources.

By 2050, it is expected that almost 70% of the global population will live in cities (settlements between 1000 and 19 999 inhabitants, depending on the country) (Satterthwaite, 2000; WWAP, 2018). Current energy-intensive, high-infrastructure water and sanitation centralized systems will be impractical for dense and high-growth megacities (Chiu et al., 2015). Mexico has, according to the 2015 intercensal survey, 119,530,753 inhabitants with 85% of the population residing in metropolitan areas and conurbations (137 in total). In 2015, 78.8% of the population lived in towns of 2,500 or more inhabitants and it is expected that by 2030 almost 125 million people will live in cities.

In summary, rapid urban growth and increases in population density combined with inequalities in water availability and consumption, contamination, lack of treatment and access to formal sanitation, and resource overexploitation demand a change from conventional centralized and linear take-dispose approaches to water resources in Mexico. Current strategies towards water management react slowly and rigidly to demographic challenges and rapid population change, often demanding high investment infrastructure and long inception times. Current urban growth outpaces the time required to design and build conventional infrastructure (WWAP, 2018). In the following section, we use three examples to describe manageable, decentralized, on-site and circular water strategies that tackle issues of water security from a socio-hydrological perspective and offer greater potential for resilience to population change.

3. New approaches and tools: metropolitan, urban and architectural scale

Based on water management and demographic challenges in Mexico, the following projects highlight water management approaches in Mexico that build SHR. These localized examples propose on-site multidisciplinary solutions, ecological integration, architecture, engineering and permaculture design features. Unlike conventional strategies, that use natural resources under a centralized and linear material economy regime, these approaches aim to utilize a local circular economy. This minimizes environmental and social impacts while maximizing the benefits to the socio-ecological systems in which they are implemented. Local-scale interventions can build resilience through the non-reliance on large-scale infrastructure (investment, governability, management and understanding through time) and through their ability to quickly adapt to climate and population change. The projects in this section are used in subsequent sections as a basis to develop a series of qualitative indicators, feedback and coupling for future policy design.

3.1. OAXACA POTENTIAL RUNOFF CATCHMENT CARTOGRAPHY

The metropolitan area of Oaxaca, located in the Central Valleys, Mexico, has changed dramatically over the past couple of centuries. Paintings and maps from the 19th Century (for example, Jose Maria Velasco – Vista de la ciudad y Valle Grande de Oaxaca) show Oaxaca had clearly defined limits, whereas today the city limits are sprawling. During this time several geographical features have been transformed: the river Atoyac no longer meanders, the hills are covered by the city and agricultural areas have disappeared. Comparison of past maps and paintings with today's city highlights how the relationship between society and the environment has changed. It also provides an opportunity to examine how a metropolis may evolve in the future.

To generate a future vision, it is crucial to understand the landscape we inhabit. From an architectural perspective, landscape can be defined as comprising the built environment and society, and their interactions with nature, both in the form of resource exploitation and enjoyment (equivalent to the natural capital concept). Landscape is seen as the materialization of complex structures that link nature and society, built throughout history. The importance of integrating landscape as a concept in the construction of future visions is crucial, especially if we consider challenges that society faces now and in the future. This ethos was the basis for an integrated future vision developed for the Central Valleys of Oaxaca. The vision used cartographic design to communicate the potential for sustainable, decentralized and resilient water management in the Metropolitan Oaxaca.

Fig. 1 Permaculture techniques in El Pedregal include dry toilets, treatment of grey waters, improved wood stoves, rainwater harvesting systems, composting, bioconstruction, regeneration of soils, terracing and groundwater recharge.

The Pedregal ravine project (Instituto de la Naturaleza y la Sociedad de Oaxaca; Foro Oaxaqueño del Agua; WWF, 2014) is a local example of a sustainable, societally focused water management programme. It is an environmental center that aims to change the culture of water management in Oaxaca with local communities. Using permaculture methods, the project attempts to recover eroded soil using terracing and planting strategies, as well as slowing rainfall runoff through various techniques such as water infiltration, collection, and distribution (Figure 1). The intention is to use the project as a replicable model for other ravines of the Central Valleys. This strategy highlights the potential for recovering eroded soil and sustainably manage rainwater with a realistic and governable model, whilst providing an alternative to water importation. The latter process is unsuitable as it relies heavily on centralized infrastructure, such as the case of Presa Paso Ancho (Instituto de la Naturaleza y la Sociedad de Oaxaca; Foro Oaxaqueño del Agua; WWF, 2014), and is based on a model of linear, intensive and competing use of water, mainly for urban and agricultural purposes.

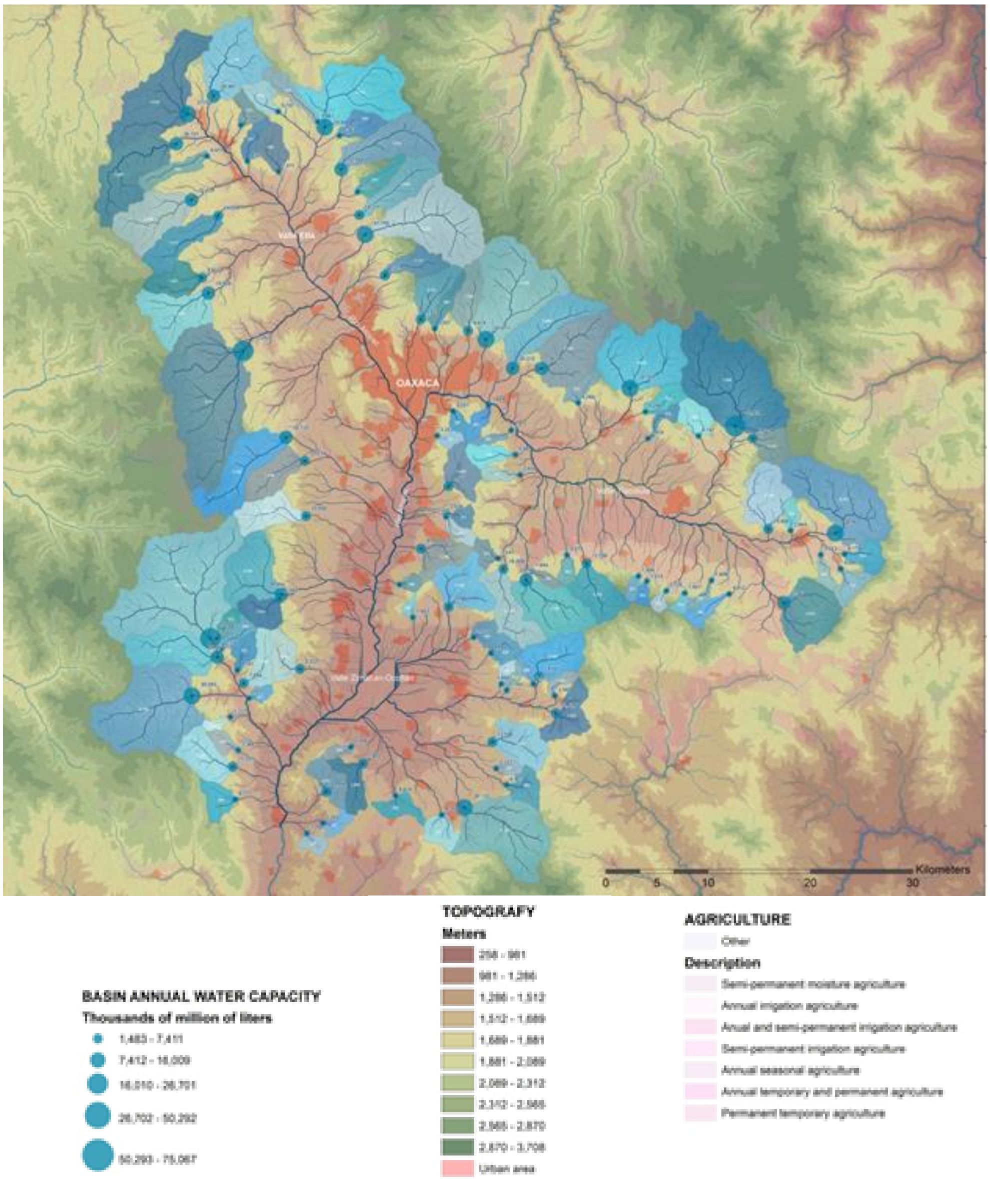

Fig. 2 Deployment of micro-dam catchment strategy in the metropolitan area of Oaxaca in the Central Valleys.

Cartographic techniques were used to create the vision for Oaxaca (figure 2), which summarize the water collection potential of sub-catchments in the Central Valleys. The vision proposes the construction of a small dam in each of the upland sub-catchments to collect rainwater. According to official calculations, the city of Oaxaca needs approximately 95,000 m^3/day of water to meet societal needs. This need is not currently met, and the future vision offers a sustainable alternative to large infrastructure projects (with high associated costs). The combined potential amount of water available is 864,000 m^3/day, based on observed rainfall and surface runoff, which suggests, at the annual-scale, there is no need for water scarcity the Central Valleys calculated with the hydrology toolset of geographic information systems (GIS) software. To ascertain the potential of each sub-catchment for water collection, rainfall was combined with a digital elevation model (DEM) to determine surface water Using the DEM as a base for the hydrology model, then Flow direction was calculated, flow accumulation and then with a defined threshold, stream order stream to feature and stream link.[2] The stream link was converted into a vector to intersect runoff with the agricultural boundaries to locate the micro-dams above the agriculture level. The watershed was calculated as the upslope area from these points (using the watershed tool from GIS) and the water accumulation with the annual rainfall from data provided by INSO. This basic calculation suggests that there is no water scarcity as such, and that on the contrary, the Central Valleys have an abundance of water, and that, for a fraction of the cost, and through smaller, easier to finance and resilient projects such as micro-dams, it would be possible to have a constant supply of water for the entire metropolitan area. This would reduce the competition with agricultural uses and achieve a more equitable distribution. At the metropolitan scale, the aggregation of these micro water catchments of blue infrastructure would build flooding resilience for the lower urban areas.

As previously stated, water availability is a key factor in water security. From a societal perspective, a region with true water scarcity is very different to one with poorly managed, but abundant water resources. The latter mindset shifts the problem from one of supply to one of distribution and decentralization, which involves civil society and the communities where water is collected, managed and distributed.

3.2. MEXICO CITY RAVINES

Recovering Waterscapes is a ravine landscape management programme designed to restore the remaining primal regions of the former valley and lake ecology in Mexico City. The project encompasses transdisciplinary research to recover ravines on the western side of the city. Developed under a close collaboration between private and public entities through a public consultation process and meetings with the local authorities and experts, it provides a spectrum of data, knowledge and expertise.

The programme was proposed as an aggregative and multiscale approach that understands the natural performance of ravines as part of a wider ecological network, fostering local and punctual interventions with metropolitan impacts. To ensure the citizens' right to live in suitable and agreeable environments, the project proposed dynamic, regulatory and prototypical interventions to rescue the ravines, both as infrastructural facilities and social spaces. It sought to re-integrate ravines into the urban fabric through the participatory engagement of agencies, communities and neighbors, building awareness and combining responsibility and ownership.

The underlying concept was the recovery of the former waterscapes in Mexico City, yet the concept was not triggered by a nostalgia of lost landscapes, but by the undergoing water crisis in Mexico City at multiple levels. The primary source of water is from boreholes, which have been linked to subsidence at a regional level as groundwater levels are lowered. The city's secondary source of water supply is imported from lower river basins located hundreds of kilometers away (Tortajada & Castelán, 2003). The city also pumps wastewater out into neighboring river systems. These unsustainable practices, together with the scarcity of water suffered by the wider metropolitan population, calls for an urgent rethink and re-understanding of the water provision and storage capabilities of the valley. Unfortunately, the potential for using ravines as green infrastructures are currently limited as they are polluted, used as sewage outlets and illegal landfill, and are invaded by informal settlements built at the risk of collapsing. Due to the informal growth of metropolitan areas, the settlements around the ravines use them as informal sanitation infrastructure, provoking ecological and soil degradation. This lack of infrastructural planning also includes lack of open and green spaces and social facilities.

The Recovering Waterscapes project uses small interventions, a hybrid of structural and non-structural micro-measures, at local scales that have a cumulative impact at the wider metropolitan scale. The interventions are grounded on basic principles: reinforcement of slopes; collection, filtering and management of water; pedestrian accessibility; and the insertion of a variety of social, commercial and community programmes, thus engaging the local community. The project understands ravines as a type of landform with specific ecological qualities (flora and fauna) and intrinsic geographical and geomorphological properties. By analyzing surface water runoff and slope properties, the potential for capturing, channeling and infiltrating water into the aquifer and the lower areas of the valley may be derived. The project challenges the established idea of developing single projects in isolation, reinforcing the intrinsic relations between all interventions. With this mentality, phasing becomes crucial, for example, hydrological performance is considered together with pedestrian accessibility and existing facilities in the neighboring areas.

The gradual aggregation of small, local-scale interventions within a wider regional vision implies a flexible strategy that adjusts to specific budgets and local contexts instead of monumental and unrealizable interventions. It generates community awareness of potential futures by the establishment of concrete projects with visible impacts at various scales. Accessibility and slope management within the ravine network gives access to local landscapes and architectonic interventions: wetland systems, planting strategies and accessibility strategies, to serve as a catalyst for the recovering of waterscapes. The architecture of proposed buildings within the project is integrated with terracing systems for soil retention and water collection, circulation, wetland treatment, filtering and storage and terraces to overview and enjoy the landscape. This landscape works as both green and blue infrastructure that recovers resilient ecology and hydrologic functions of the ravine. This also improves the capacity of these neighborhoods to adapt to climate change. By managing and cleaning the illegal disposal and landfill of the ravine, the project prevents water-borne diseases and the filtering of pollution into groundwater resources.

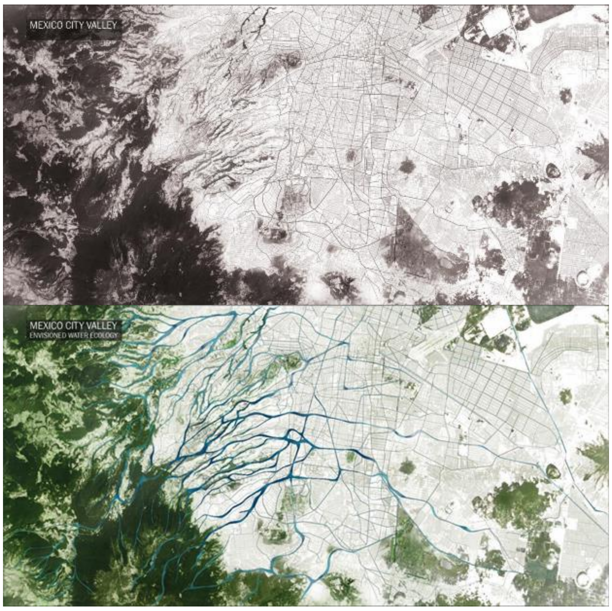

Fig. 3 Envisioning Mexico City's future: asphalted city (a) versus systemic ravine regeneration, green and blue infrastructure and quality open spaces (b).

At the architectural scale, buildings are able to form part of the ravine regeneration. For example, a community and environmental center was designed to have commercial facilities and provide easy access to the upper part of the ravine. The building generates a viewing terrace from which a water treatment itinerary starts, finishing in a rainwater collection pond and urban agricultural allotments. The terraces and access paths work as retaining structures to prevent landslides. At the metropolitan scale of Mexico City, the gradual reintegration of ravines into the valley's water cycle allows groundwater recharge, bringing to life other hydrological features (ravines, rivers, lakes, etc.), improving the quality of the air by increasing the humidity levels, and providing inhabitants natural access to water and the opportunity to engage with the new socio-hydrological landscape. If we scale up the impacts of these local interventions to the metropolitan scale, we can see a feedback effect at the larger scale (figure 3). The production of maps and other media allow a radically different strategy for Mexico City to be shared with the local communities for educational and participatory purposes.

3.3. SANITATION ECOTECHNOLOGIES IN URBAN COMMUNITIES

As previously mentioned, water availability in Mexico is greatly compromised by chronic pollution of its natural water bodies. Once the problem of water provision is addressed, the methods for managing and treating wastewater have the potential to compromise the benefits of making water accessible. In this case study, we describe the sanitation component of an urban, community-based project at the Metropolitan Autonomous University, Cuajimalpa Campus (UAM-C), in Mexico City. To satisfy human needs in the context of a local circular economy, an ecotechnology was implemented that minimizes the environmental impact and generation of waste while maximizing the benefits to socio-ecological systems.

Current sustainable sanitation trends include on-site technologies, such as composting dry toilets. So far, decentralized sanitation ecotechnologies have been developed for mostly rural or marginalized peri-urban areas. The need to urbanize these ecotechnologies is urgent, however, multiple studies show that the general public has a negative perception of on-site systems, since centralized sewer systems are equated with better social status and seen as the responsibility of the State, rather than self-management activities (Roma, Philp, Buckley, Xulu, & Scott, 2013). In addition to the negative perception, they are also highly sophisticated bio-based technologies, which require the users, who are also operators, to have adequate technical knowhow to efficiently use, monitor, operate, maintain, and manage these solutions.

A programme was developed specifically for informing an urban population about the benefits of ecotechnological sanitation solutions, as well as supporting the transformation of its culture and habits through participatory and face-to-face methodologies for the co-design, implementation, and operation of an urban urine-diversion dry toilet (UDDT) prototype. Two different disciplines were coupled for this purpose: Social Studies for the adoption of sustainable sanitation values and technologies via participatory methods and Biological Engineering for the sizing, operation, monitoring and maintenance of an urban UDDT. It is fundamental that both disciplines are involved to guarantee the true adoption of UDDTs. The programme was divided into three phases: diagnosis and promotion; design and prototype; and evaluation of its adoption. The first phase included conducting qualitative research via participatory methodologies to diagnose community perception of sanitation in general and UDDTs specifically. This fieldwork was carried out by a work-group comprised of approximately 35 members of the university's community, mostly students from different bachelor programmes, a few professors and campus workers. The diverse makeup of the group was such as to improve the range of impact on all sectors of the university. This group was trained in ecotechnologies, participatory methodologies and promotional skills needed to reach out to the rest of the university.

Fig. 4 UDTT Prototype

The second and third phases took place during the second year of the programme. The second phase included establishing the social, cultural and technological design objectives with students of different bachelor programmes: Biological Engineering, Molecular Biology, Design and Socioterritorial Studies. Also, using Social Innovation and Design Thinking approaches, the technological sanitation solution was jointly selected. Moreover, the architectural layout of the built space to house the UDDT, the Laboratory of Dry Toilets (LABS) was co-designed with these students in collaboration with an expert who specializes in bioconstruction and ecotechnologies. The UDDT's technological conceptual and final design, standardized operating procedures (SOPs) for the operation, maintenance and monitoring, as well as the scale-up plans were developed by biological engineering and molecular biology undergraduate students. The second phase also included building the LABS out of cob and ferrocement by the community to foster its connection to the UDDT prototype. The permaculture features of the co-designed LABS and UDDT include Vietnamese-style chambers, greywater treatment biofilters, rainwater harvesting, solar-aided humanure composting, and air extraction with solar heating.

In the final phase, the degree of socio-technological transformation (UDDT adoption) in the project's workgroup (35 students) was measured via an anonymous survey. The survey had three objectives: Firstly to establish the level of knowledge obtained regarding the project's main themes (waste and wastewater source separation, waste biomass valorisation and the selected ecotechnologies); secondly, the change in values with respect to waste biomass and wastewater, and their perception as resources; and finally the change in actions due to a change in values. Based on the survey results, this study achieved a significant socio-technological transformation within the community involved in the project (see Table 1).

Table 1. Evaluation of the degree of adoption of the decentralized sanitation solution by an urban university community (socio-technological transformation)

Reported Transformation and Change in Perceptions	**Surveyed Population**
Change every-day waste biomass management habits (incorporated source separation, reusing or composting, waste/wastewater reduction)	83%
Inform of and influence waste biomass management habits in close social circles	70%
Consider participatory methodologies effective to enhance adoption of sustainable sanitation solutions	80%

4. A novel approach to assessing resilience through socio-hydrological indicators

If the three previous case studies are to serve as a model for future approaches to water management, a set of multidisciplinary indicators are required to guide their implementation and maintenance, and to assess their impacts. In this section, we outline a set of integrated qualitative indicators with the potential to gauge SHR. The indicators go beyond the efficient management of the quantity and quality of hydrological resources to include impacts on society. SHR implies the integration of diverse viewpoints, from ethical and cultural perspectives to the long-term goals and needs of present and future generations. Currently, there are tools in economics, management and engineering that aid administration of multiple resources over time. However, due to the systemic and comprehensive nature of resilience, it is important to identify, incorporate and evaluate parameters from a range of disciplines. This cross-discipline approach allows simultaneous correlation over extended periods of time and can impact economic growth, community social development, productivity, preservation and protection of the environment.

In determining the linkage between social resilience (SR) and water security for the design of sustainable urban metropolitan infrastructure, and considering the SHR concept, potential SR indicators are considered. We use SHR to guide the exploration of SR indicators where climate and population change, water security and management are contemplated for the design of urban metropolitan contexts. Establishing the right parameters and their corresponding indicators is necessary to develop effective, resilient, strategic planning. This is because indicators act as vectors, notifying the magnitude and the direction of a parameter, which in turn can illustrate how close it is from the destination point and how quickly it is reaching or distancing away from that point. To move from novel approaches towards a socio-hydrological resilience diagnosis, policies, plans, programs and projects must include indicators in order to measure their efficiency. Resilience indicators give rise to information and documentation systems, which can then be used for fact-based decision making, strategic planning and management of a region, community or company. In addition to this, looking at projects from a common indicator framework fosters knowledge exchange based on various experiences and strengthens national socio-hydrological resilience.

4.1.1. Formulation of socio-hydrological resilience indicators: recommendations

Considering SHR is a nascent discipline, both as a research field and as a professional activity in municipalities and industry, resilience indicators are only beginning to be developed and understood. Nonetheless, we can extrapolate the theoretical frameworks from related fields like environmental, sustainability, energy and eco-efficiency indicators to formulate SHR indicators. Here we summarise recommendations on indicator construction and, in the rest of this section, we outline qualitative indicators that could be further developed as quantitative indexes in the near future.

In the case of eco-efficiency, indicators are constructed as rates that integrate engineering and financial parameters, where the numerator includes an impact, such as the resource consumption or polluting emissions, and the denominator represents the resulting level of production or benefit, in physical (product unit) or financial (value added, profit) terms. The calculation of indicators can be furthered normalized (e.g., per one kilo of product or one dollar of value) and following a rule that the lower the metric the more effective the process is. A low value indicates greater benefit or productivity, that the impact of the process is lower (the numerator is smaller) or that the output of the process is greater (the denominator is greater) (Schwarz, Beloff, & Beaver, 2002). In this manner, resilience indicators as rates could combine parameters from different fields (social, cultural, environmental, economic, scales of time and space, etc.) while establishing what the magnitude and direction of change mean for the resilience of a given system. In addition, indicators should be designed to be: simple, so as not requiring significant amounts of time and resource to be produced; useful, whereby they can convey sufficient information for adequate decision making and planning; understandable, where they can be properly interpreted by a range of sectors and stakeholders (neighbors, municipality and industry professionals, etc.); cost-effective (in terms of data collection); reproducible, incorporating standards to produce consistent and comparable results; robust, so as to indicate the progress towards resilience in multiples scenarios; and stackable (across processes and time), so that they may be useful beyond the process or time for which the calculation was made.

4.1.2. Multiscale SHR qualitative indicators and their weighting

We use an alphabetically-based taxonomy system to describe the weighting method applied to the qualitative indicators. ‘A’ is an essential indicator to achieve SHR, ‘B’ is a required field that can only be discarded exceptionally if it does not apply to the nature of the project, ‘C’ are recommended aspects when pursuing SHR, ‘D’ are preferable aspects for SHR and ‘E’ are part of good practices that give extra dimensions to SHR. Table 2 summarizes the proposed multiscale SHR indicators and their weighting. At the smaller scales of intervention, it is important to consider the possible feedback impacts at the larger scales and vice versa, the possibility of decentralizing large-scale proposals to build resilience across scales.

Table 2. Qualitative indicators for SHR from multi-scalar case studies.

			Metropol **Oaxaca**	*Urban* **Mexico ravine**	*Archit.* **LABS UDDT. Mex.**	*weight*
SOCIAL (economy and governance)	GOVERNANCE*	Decentralized, adaptive governance	□	□	□	A
		Prototypical, summative interventions	□	□	□	B
		Legal framework	□	□	□	C
		Delineated responsibility and authority (inc autonomy)	□	□	□	C
		Phasing strategies and short to long-term management and contingency		□		C
	RESOURCE	Fair distribution of resources	□	□		A
		On-site water resources rather than off-site exploitation	□	□	□	B
		Agricultural production resource sharing	□			E
	COMMUNITY**	NGOs, civil society integration	□			D
		Self-building, on-site tech, micro-infrastructure, leadership and community initiatives	□	□	□	C
		Social participation		□	□	A
		Address economic, social and professional resistances and motivations			□	B
		Educational (socio-ecosystem, local economy, conventional and innovative solutions)			□	B
		Values and habit changing (reduction in water/wastewater demand, circular local water management)			□	A
		User feedback, ability to cope with changes			□	C
	MAINTENANCE	Data and information gathering and management about the system follow up and maintenance	□	□		B
	HEALTH	Health benefits, pollution reduction	□	□	□	C
	ECONOMY	Generation of new economies		□		A
		Water savings		□	□	B
	URBAN	Accessible ecosystem open and green spaces	□	□		A
		Community facilities		□	□	D

(Table 2. Continuation)

			Metropol **Oaxaca**	*Urban* **Mexico ravine**	*Archit.* **LABS UDDT. Mex.**	*weight*
WATER SECURITY (supply and waste)		Constant supply during draughts				A
		Circular metabolism				A
		Water quality				A
		Multiscalar basin management				A
		Wastewater treatment and recycling				B
		Rainwater harvesting				B
		Green space maintenance				C
		Pressure reduction on wastewater infrastructure				C
		Hybrid micro-scale structural and non-structural measures				D
		Micro-scale structural measures (risk reduction and adaptability)				C
		Non-structural measures (Biofilters)				B
		Green and blue infrastructure				A
		Operational and maintenance capacity				B
HYDROLOGY (ecology and environment)	CLIMATIC EVENTS	Climate change adaptation				A
		Soil retention				C
		Flooding prevention				B
	POLLUTION	Filtering and aquifer recharge				C
		Ecosystem restauration and decontamination				B
		Water-borne disease prevention				B
	HUMAN IMPACT	Mitigation of human-induced microclimate changes (e.g. heat-island effect)				B
<< >> Multiscalar feedback integration system << >>						B

* (Milman & Short, 2008) ** (Cordova & Knuth, 2005)

4.1.3. Socio-hydrological resilience coupling

The list of qualitative indicators (Table 2) is divided into three main sections: hydrological environment, water security and social aspects. In order to achieve a balance between the socio-hydrological indicators, we propose a scatter-chart-based method to evaluate the interdependencies between coupled parameters (Wurl et al., 2018). To assess this integration, we have selected the main parameters weighted as ‘I’ in Table 1. On the ‘X’ axis are parameters related to water security and environments and on the ‘Y’ axis those related to social resilience (see Table 3). As an example of usage: in pair ‘IV’, water quality improvement projects cannot be proposed in isolation from projects related to social habits or consumption reduction; in pair ‘VI’, socio-economic development cannot be planned in isolation from circular metabolism; in pair ‘II’, decentralized governance has to be co-related to multi-scalar water systems; governance needs to have the capacity to comprehend and act on entire hydrological systems such as ravines, basins, valleys, etc. In the case of pair ‘I’, climate change cannot be addressed without community involvement or constant supply in the ‘III’ case, must go hand in hand with a fair distribution of that constant supply.

Table 3. Socio-hydrological coupling of ‘A’ indicators

Socio-economic development						VI
Ecosystem accessibility					V	
Habit/ Econ. reduction				IV		
Equal distribution of resources			III			
Decentralized government		II				
Social participation	I					
	Climate change adaptation (flooding, droughts, soil)	Multiscalar basin management	Constant supply during draughts	Water quality	Green and blue infrastructure (aquifer recharge, soil retention, ecosystem restoration)	Circular metabolism

With X and Y quantified, a scatter chart may be used to locate points A to F, according to their X (water resilience) and Y (social resilience) coordinates (Fig. 2a). This process allows a balanced coupling area of a 20% deviation to be defined from a 50-50 socio-hydrological relationship. A distribution of points outside the balanced coupling area would mean a disproportion between the social and water resilience. For example, a huge infrastructural dam for water supply that does not encompass a fair distribution strategy. A concentration of points in the diagonal area of the chart means the proposal is balanced and its low or high evaluation depends on the (left or right respectively) tendency of the points as shown in Figure 3.

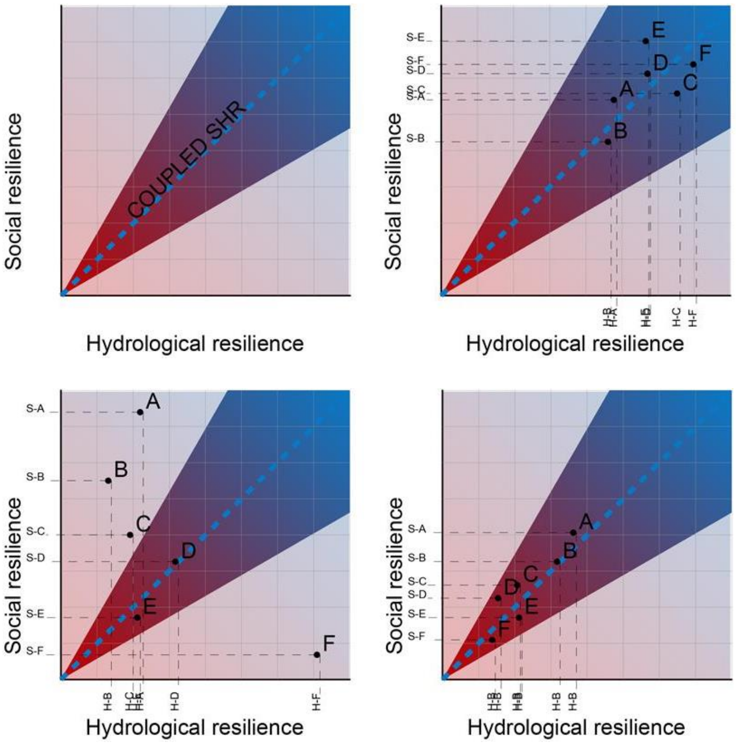

Fig. 3 (a) SHR coupling area definition in scatter chart scenarios, (b) well balanced and high SHR, (c) an unbalanced SHR, (d) well balanced but low SHR.

4.1.4. Conclusions: potential for socio-hydrological resilience in transdisciplinary and collaborative approaches

This manuscript has set the basis for larger multi-disciplinary research into methods of assessing the incipient notion of SHR. Metropolitan landscapes are inescapably socio-hydrological. Contemporary conditions of rapid urbanization and climate change threaten water security which we, and the referred literature, propose must be addressed from the integrated, decentralized and circular perspective of SHR. Existing practices in Mexico, water availability, pollution combined with the rapid growth pace of urban populations requires a paradigm shift in water management practices and their social implications. The inherently dynamic, complex and extensive human interactions with ecosystems demand a transformation to sustainable ecosystem management. '[D]eveloping and maintaining 'beneficial interactions between managed and natural systems' is necessary and 'avoiding these interactions is no longer a practical option' (Ellis & Ramankutty, 2008).

We propose the concept of socio-hydrological resilience as a new approach to analyze water management in urban areas of Mexico. This approach contributes to the usual management of water, which currently focuses on the administration of physical infrastructure for urban systems and the collection, treatment, distribution and collection of wastewaters in cities. We provide a novel perspective to understand the problems related to water access, quality of water, water demand and water governance in urban spaces as issues intrinsically related. Due to an intense urbanization process in Mexico, identifying the components of the human-water system that enable the socio-hydrological resilience of cities to address uncertainty and changes in water availability is crucial.

We provide a theoretical, qualitative and retrospective analysis of traditional practices and emerging approaches, such as socio-hydrological resilience, which allows analyzing human-water systems and subsystems, and thereby offer evidence to support management and water security in specific cases. To this end, we build a series of indicators that will allow resilience assessments for urban environments in different scenarios in the future, regarding water use (supply and demand), access to water, natural disasters (droughts, floods) and climate change in the cases described. The socio-hydrological resilience approach is a theoretical and practical framework under construction since there is not enough evidence reported in the literature and each author evaluates different elements of human-water systems and subsystems. Unlike previous socio-hydrological resilience research, we consider water security objectives in the combined water-human system as an appropriate approach to design strategies for integrated and resilient management of water resources. Likewise, we develop a method that highlights the interrelationships between communities and natural resources, which tend to be uncertain, complex and subjective when the plurality of perspectives of interested groups, governments and individual stakeholders is involved.

Addressing these complex interactions requires input from various disciplines, combining metropolitan design and decision-making with the engagement of local communities, civil society and governmental bodies. Communication, transparency, education and change of habits are social aspects that ensure the involvement of local communities. Therefore, we propose an outline for three groups of qualitative indicators, social resilience, water security and hydrological environments, to ensure social participation and transdisciplinary integrated evaluation of water management proposals in metropolitan environments. To ensure the integrated relationship of these three groups, we propose a coupling scatter that assesses the balance of the social and the hydrological aspects of future projects. This manuscript forms the basis for a potential new branch of transdisciplinary research.

Acknowledgments
This work was funded in part by the joint UK-NEWTON Fund and Mexico's National Council of Science and Technology (abbreviated CONACYT) grant for the project 'Enhancing regional water security in semi-arid regions through improved metropolitan design'. Dr. Garcia-Becerra's work is funded by CONACYT Researcher-Professor Fellowship (Project No. 2989). In addition, the authors would like to thank the UAM-C community for their acceptance of and participation in the UDDT project, and to the UAM-C rectory for its financial support. Also, we gratefully acknowledge the collaborators from Mexico City, UNAM, Territorios, Groundlab team and the communities who participated in the public consultancy as well as the participants of the AA Visiting School workshop in Oaxaca and the local NGOs Casa de la Ciudad and Instituto de la Naturaleza, without whom this work could not have been possible. Finally, we also thank the reviewers of this chapter for the insightful comments and clarifications.

References

Adger, W. N. (2000). Social and ecological resilience: are they related? *Progress in Human Geography*, *24*(3), 347–364. https://doi.org/10.1191/030913200701540465

Aniello, C., Morgan, K., Busbey, A., & Newland, L. (1995). Mapping micro-urban heat islands using LANDSAT TM and a GIS. *Computers & Geosciences*, *21*(8), 965–969. https://doi.org/10.1016/0098-3004(95)00033-5

Arnell, N. W. (1999). Climate change and global water resources. *Global Environmental Change*, *9*, S31–S49. https://doi.org/10.1016/S0959-3780(99)00017-5

Arnell, N. W., & Gosling, S. N. (2016). The impacts of climate change on river flood risk at the global scale. *Climatic Change*, *134*(3), 387–401. https://doi.org/10.1007/s10584-014-1084-5

Blair, P., & Buytaert, W. (2016). Socio-hydrological modelling: a review asking "why what and how?" *Hydrology and Earth System Sciences*, *20*(1), 443–478. https://doi.org/10.5194/hess-20-443-2016

Brenner, N., & Schmid, C. (2011). Planetary Urbanization. In M. Gandy (Ed.), *Urban Constellations* (pp. 10–14). Jovis.

Cheng, C.-L. (2002). Study of the inter-relationship between water use and energy conservation for a building. *Energy and Buildings*, *34*(3), 261–266. https://doi.org/10.1016/S0378-7788(01)00097-4

Chiu, Y.-R., Tsai, Y.-L., Chiang, Y.-C., Chiu, Y.-R., Tsai, Y.-L., & Chiang, Y.-C. (2015). Designing Rainwater Harvesting Systems Cost-Effectively in a Urban Water-Energy Saving Scheme by Using a GIS-Simulation Based Design System. *Water*, *7*(11), 6285–6300. https://doi.org/10.3390/w7116285

Ciullo, A., Viglione, A., Castellarin, A., Crisci, M., & Di Baldassarre, G. (2017). Socio-hydrological modelling of flood-risk dynamics: comparing the resilience of green and technological systems. *Hydrological Sciences Journal*, *62*(6), 880–891. https://doi.org/10.1080/02626667.2016.1273527

CONAGUA. (2017). *Statistics on Water in Mexico 2017 Edition*. Mexico City.

Connett, P. (2013). Zero waste 2020: Sustainability in our hands. In *Motivating Change: Sustainable Design and Behaviour in the Built Environment*. https://doi.org/10.4324/9780203482087

Cordova, A., & Knuth, B. A. (2005). Barriers and strategies for dry sanitation in large-scale and urban settings. *Urban Water Journal*, *2*(4), 245–262. https://doi.org/10.1080/15730620500386511

de Kraker, J. (2017). Social learning for resilience in social–ecological systems. *Current Opinion in Environmental Sustainability*, *28*, 100–107. https://doi.org/10.1016/j.cosust.2017.09.002

Ellen MacArthur Foundation. (2015). Why the circular economy matters. *Delivering the Circular Economy: A Toolkit for Policymakers*, 19–32.

Ellis, E. C., & Ramankutty, N. (2008). Putting people in the map: anthropogenic biomes of the world. *Frontiers in Ecology and the Environment*, *6*(8), 439–447. https://doi.org/10.1890/070062

Folke, C. (2006). Resilience: The emergence of a perspective for social–ecological systems analyses. *Global Environmental Change*, *16*(3), 253–267. https://doi.org/10.1016/j.gloenvcha.2006.04.002

Frumkin, H. (2002). Urban Sprawl and Public Health. *Public Health Reports*, *117*(3), 201–217. https://doi.org/10.1093/phr/117.3.201

Garcia-Becerra, F. Y., & Ortiz, I. (2018). Biodegradation of Emerging Organic Micropollutants in Nonconventional Biological Wastewater Treatment: A Critical Review. *Environmental Engineering Science*, ees.2017.0287. https://doi.org/10.1089/ees.2017.0287

Grey, D., & Sadoff, C. W. (2007). Sink or Swim? Water security for growth and development. *Water Policy*, *9*(6), 545–571. https://doi.org/10.2166/wp.2007.021

Houdret, A., Kramer, A., & Carius, A. (2010). The water security nexus: challenges and opportunities for development cooperation. *The Water Security Nexus: Challenges and Opportunities for Development Cooperation*. https://www.cabdirect.org/cabdirect/abstract/20113162024

Instituto de la Naturaleza y la Sociedad de Oaxaca; Foro Oaxaqueño del Agua; WWF. (2014). *Un plan común para un bien común*. Oaxaca. ttps://docs.wixstatic.com/ugd/8eed4e_e51e488c2e1d4af3b2478dd7c68e6890.pdf

Jothiprakash, V., & Sathe, M. V. (2009). Evaluation of Rainwater Harvesting Methods and Structures Using Analytical Hierarchy Process for a Large Scale Industrial Area. *Journal of Water Resource and Protection*, *01*(06), 427–438. https://doi.org/10.4236/jwarp.2009.16052

Langridge, R., Christian-Smith, J., & Lohse, K. A. (n.d.). Access and Resilience: Analyzing the Construction of Social Resilience to the Threat of Water Scarcity. *Ecology and Society*. Resilience Alliance Inc. https://doi.org/10.2307/26266027

Lee, J., Pedersen, A. B., & Thomsen, M. (2014). Are the resource strategies for sustainable development sustainable? Downside of a zero waste society with circular resource flows. *Environmental Technology and Innovation*. https://doi.org/10.1016/j.eti.2014.10.002

Mao, F., Clark, J., Karpouzoglou, T., Dewulf, A., Buytaert, W., & Hannah, D. (2017). HESS Opinions: A conceptual framework for assessing socio-hydrological resilience under change. *Hydrology and Earth System Sciences*, *21*(7), 3655–3670. https://doi.org/10.5194/hess-21-3655-2017

Meinzen-Dick, R., & Appasamy, P. P. (2002). Urbanization and intersectoral competition for water. *Woodrow Wilson International Center for Scholars Environmental Change and Security Project (Ed.) Finding the Source: The Linkages Between Population and Water. Washington, DC, The Woodrow Wilson Institute*, 27–51. http://www.wilsoncenter.org/sites/default/files/popwawa3.pdf

Méndez-Lemus, Y., & Vieyra, A. (2014). Tracing Processes in Poverty Dynamics: A Tale of Peri-urban Small-scale Farmers in Mexico City. *Urban Studies*, *51*(10), 2009–2035. https://doi.org/10.1177/0042098013505923

Milman, A., & Short, A. (2008). Incorporating resilience into sustainability indicators: An example for the urban water sector. *Global Environmental Change*, *18*(4), 758–767. https://doi.org/10.1016/j.gloenvcha.2008.08.002

Panebianco, S., & Pahl-Wostl, C. (2006). Modelling socio-technical transformations in wastewater treatment—A methodological proposal. *Technovation*, *26*(9), 1090–1100. https://doi.org/10.1016/J.TECHNOVATION.2005.09.017

Patz, J. A., Campbell-Lendrum, D., Holloway, T., & Foley, J. A. (2005). Impact of regional climate change on human health. *Nature*, *438*(7066), 310–317. https://doi.org/10.1038/nature04188

PUEC UNAM. (2010). *Evaluación externa del diseño e implementación de la política de acceso al agua potable del Gobierno del Distrito Federal*. Ciudad de Mexico. http://data.evalua.cdmx.gob.mx/files/recomendaciones/evaluaciones_finales/inf_agu.pdf

Puppim De Oliveira, J. A., Doll, C. N. H., Kurniawan, T. A., Geng, Y., Kapshe, M., & Huisingh, D. (2013). Promoting win-win situations in climate change mitigation, local environmental quality and development in Asian cities through co-benefits. *Journal of Cleaner Production*. https://doi.org/10.1016/j.jclepro.2013.08.011

Roma, E., Philp, K., Buckley, C., Xulu, S., & Scott, D. (2013). User perceptions of urine diversion dehydration toilets: Experiences from a cross-sectional study in eThekwini municipality. *Water SA*. https://doi.org/10.4314/wsa.v39i2.15

Rosalva Landa. (2014). *El acceso y uso del agua en México*. Mexico City. https://ceiba.org.mx/publicaciones/rosalvalanda/acceso_agua.pdf

Saja, A. M. A., Teo, M., Goonetilleke, A., & Ziyath, A. M. (2018). An inclusive and adaptive framework for measuring social resilience to disasters. *International Journal of Disaster Risk Reduction*, *28*, 862–873. https://doi.org/10.1016/j.ijdrr.2018.02.004

Satterthwaite, D. (2000). Will most people live in cities? *BMJ (Clinical Research Ed.)*, *321*(7269), 1143–1145. http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=PMC1118907

Schwarz, J., Beloff, B., & Beaver, E. (2002). Use sustainability metrics to guide decision-making. *Chemical Engineering Progress*. https://doi.org/10.1088/0957-0233/26/4/045104

Shaw, D., Scully, J., & Hart, T. (2014). The paradox of social resilience: How cognitive strategies and coping mechanisms attenuate and accentuate resilience. *Global Environmental Change*, *25*, 194–203. https://doi.org/10.1016/j.gloenvcha.2014.01.006

Strande, L., Ronteltap, M., & Brdjanovic, D. (Eds.). (2014). *Faecal sludge management: systems approach for implementation and operation* (1st ed.). London, UK: IWA Publishing.

Tortajada, C., & Castelán, E. (2003). Water Management for a Megacity: Mexico City Metropolitan Area. *Ambio*. SpringerRoyal Swedish Academy of Sciences. https://doi.org/10.2307/4315348

UN. (2013). *Water Security and the Global Water Agenda A UN-Water Analytical Brief*. Ontario, Canada. http://www.unwater.org/publications/water-security-global-water-agenda/

UNESCO-IHP. (2012). *Strategic Plan of the eighth phase of IHP (IHP-VIII, 2014-2021)*. Paris. http://unesdoc.unesco.org/images/0021/002180/218061e.pdf

Wurl, J., Gámez, A. E., Ivanova, A., Imaz Lamadrid, M. A., & Hernández-Morales, P. (2018). Socio-hydrological resilience of an arid aquifer system, subject to changing climate and inadequate agricultural management: A case study from the Valley of Santo Domingo, Mexico. *Journal of Hydrology*, *559*, 486–498. https://doi.org/10.1016/j.jhydrol.2018.02.050

WWAP (United Nations World Water Assessment Programme). (2018). *2018 UN World Water Development Report, Nature-based Solutions for Water*. Paris. http://unesdoc.unesco.org/images/0026/002614/261424e.pdf

Zaman, A. U. (2015). A comprehensive review of the development of zero waste management: lessons learned and guidelines. *Journal of Cleaner Production*, *91*, 12–25. https://doi.org/10.1016/J.JCLEPRO.2014.12.013