Index insurance as a risk management strategy to hydrological extremes for water utilities

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Key Points:

- Index insurance helps reduce risk and maintain financial stability by protecting water supply companies' business or compensate end user.
- Improving the application of index insurance in the water sector by incorporating water pollution and flood risks is still necessary.
- To implement this tool, more studies of extreme's events relationships, their implications in financial losses, among others, is needed.

Abstract

As the global economy expands, increasing losses of natural capital translate into substantially higher costs and inefficiencies in achieving future water security. Risk transfer is one risk management tools used to protect regions particularly vulnerable to the effects of extreme events that affect water availability. Index insurance has been investigated as a potential solution for dealing with drought events that lead to water scarcity in the water supply sector. Nonetheless, water scarcity can result not only from drought but also from the degradation of quality. Floods also have an impact on water supply, resulting in economic losses for the supply sector. Water supply services are under threat from a variety of hazards intensified by extremes of climate variability and climate change and socioeconomic factors. This work aims to discuss index insurance adaptation to cover financial losses incurred by water utility companies as a result of a variety of extreme hydrological events and uncertainty drivers, bringing opportunities to improve index insurance application to the sector. Given the complex vulnerability to different hazards related to the quantity and quality of raw water, in addition to the drivers of uncertainty affecting water availability, improved risk transfer model application is still required to incorporate such multiple risks and uncertainties. Many gaps and limitations in the design and implementation of water infrastructure insurance remain, including improved characterization of the relationship between droughts, floods, and pollution extremes and their implications in financial losses for supply; and the development of damage quantification methodologies, among other issues.

1 Introduction

Water security is defined as the availability of water in sufficient quantity and quality to meet human and economic needs, as well as the conservation of aquatic ecosystems with an acceptable level of risk from extreme events (ANA, 2022). According to UNEP (2021), water insecurity is the second most vulnerable aspect to the effects of climate change in the eyes of the Paris agreement signatory countries. Water availability in quantity and quality has changed as a result of human activity development, and, at the same time, climate change has an impact on the hydrological cycle, increasing vulnerability to natural disasters and extreme events. Climate change is expected to exacerbate future heavy precipitation and drought conditions in many parts of the world due to changes in precipitation patterns, altered snowfall and melting regimes, and increased evapotranspiration (Satoh et al., 2022). Increased runoff and stormwater overflow from heavy rainfall over saturated catchments can transport pollutants to surface waters, increasing pathogens, turbidity, nutrients, and organic matter concentrations (Nijhawan & Howard, 2022). Furthermore, unruly land use can degrade water quality and harm public health by allowing pollutants to enter without being adequately treated (Sonobe et al., 2019). Under the same perspective, unplanned land use change can also have an impact on the hydrological cycle, and, thus, water availability (Anand et al., 2018).

Water availability declines can jeopardize the sustainability of other dependent services such as food security, energy supply, and consumer goods (UN-Water, 2021). As a result, such changes affect the risk of capital derived from the use of natural resources, which affects the concern of risk-averse individuals (Kelsall et al., 2022). As the global economy expands, increasing losses of natural capital translate into substantially higher costs and inefficiencies in achieving future water security (Vörösmarty et al., 2021). Risk management, according to (Kreibich et al., 2022), generally reduces the impacts of extreme weather and climate events. Risk transfer is one of the risk management tools that has been used to protect regions highly vulnerable to the impacts of extreme events, which are exacerbated by climate and land use and cover change (Benso et al., 2022; Navarro et al., 2021), in addition to demand changes caused by population growth (Guzmán et al., 2020). A functional insurance scheme can provide financial relief, which, when combined with adequate risk education and awareness, can result in a higher income situation (Mohor & Mendiondo, 2017).

The insurance market has shown significant impacts on improving public infrastructure risk management (Agrawal & Kim, 2022). Different from conventional insurance schemes that rely on loco-verifiable losses, index insurance relies on the observation of an index that is closely related to losses (Miranda & Farrin, 2012). Indexed insurance stands out as a risk transfer option because it reduces administrative costs by not requiring loss verification, making it more affordable for poorer regions, where insurance availability remains significantly lower than the global average (OECD, 2021). Since the losses are determined by the index value, if policyholders take other measures to mitigate their losses during an extreme event, they will receive the amount agreed upon in the contract. This creates conditions to reduce moral hazards and adverse selection problems (Clement et al., 2018).

Given the revenue losses associated with multiple droughts over several years or extended multiyear droughts in the water supply sector, index insurance is a recently studied alternative to cover loss and damage, in light of the challenges associated with an expansion of large supply capacities to meet cover demand during drought (Baum et al., 2018; Baum & Characklis, 2020; Guzmán et al., 2020; Zeff & Characklis, 2013). Index insurance, according to Zeff & Characklis (2013), is an alternative to be taken isolated or combined with temporary conservation measures, such as restrictions on specific types of water uses or surcharges and contingency funds.

According to Zeff & Characklis (2013), index insurance is beneficial when the cost of mitigating high-cost and low-frequency drought events would require the maintenance of significant and infrequently used contingency funds, especially in the face of the increased water availability instability intensified by climate and land use changes. However, one limitation of index insurance implementation during high-cost drought extremes is the need to maintain large reserves, which raises the insurer's policy implementation costs. Further, this limitation, according to Baum & Characklis (2020), can be overcome through risk pooling and reinsurance strategies. The literature also brings examples of tailored contracts during drought: Guzmán et al. (2020) estimated the police prices to the utility during drought in the face of climatic, anthropogenic, and economic change drivers and found that insurance contracts that cover only longer droughts offer better financial performance than contracts that cover all types of drought duration.

Water scarcity, on the other hand, can result not only from a lack of water in terms of quantity, but also from the degradation of quality. The treatment process's efficiency is highly dependent on the quality of the raw water (Thorne & Fenner, 2011). As a result, deterioration in water quality can cause failures in the treatment process, with consequences for health and supply reliability (Raseman et al., 2017), as well as interruptions and financial losses for the company. In addition to changes in water quality, floods also impact water supply in the process of capturing, adducting, and distributing water, resulting in economic losses for the supply sector (Milograna et al., 2013).

For the water supply sector, index insurance has been recently studied for drought. However, to the best of our knowledge, there is little evidence in the literature of suggestions or proposals for implementing risk transfer measures that assist water supply companies in managing other types of extreme events, such as floods and pollution extremes, as well as their interaction. Additionally, driver factors of uncertainty in water availability and demand affect the water supply sector and lead to a high degree of ambiguity in the appropriate premium for index insurance schemes (Guzmán et al, 2020). The multihazard nature of threats to water supply service and the role of driven factors in intensifying the occurrence of such extreme events that affect water supply provision should be discussed further in relation to all of these prerogatives. This discussion opens the door to expanding the use of risk transfer models as an alternative to hedge against water utility financial losses in a changing environment, taking into account a multi-hazard perspective. This work aims to discuss why and how index insurance frameworks can be adapted to cover financial losses incurred by municipal, state or private water utility companies because of a variety of extreme events and uncertainty drivers (which we call hereafter of multidrivers), besides bringing opportunities to improve index insurance application to the water supply sector through a critical literature analysis.

2 Theoretical background

2.1 Climatic drivers impacting water supply

2.1.1 Climate change impacts on hydrological extreme events

One of the great challenges of the 21st century is to understand how climate change will impact the hydrological cycle. As a result, the first question in the 23 unsolved problems in hydrology (UPH) is related to the accelerating/decelerating of the hydrological cycle under global warming (Blöschl et al., 2019). Despite the unanswered question in terms of the method - "how", scientists agree that climate change has affected and will continue to affect the hydrological cycle. According to the Intergovernmental Panel on Climate Change report (IPCC, 2022), the hydrological cycle has been intensified by climate change, and more people are exposed to extreme water-related events such as floods and droughts. This higher exposure exacerbates the water-related vulnerabilities, increases water insecurity and can negatively impact freshwater and terrestrial ecosystems, including regions already experiencing severe water stress.

Rising temperature, decreasing precipitation, and increasing open water evaporation are among the range of climatic factors responsible for decreasing inflows that have been reported in several cases around the world observed by Gravity Recovery and Climate Experiment (GRACE) satellite data (J. Wang et al., 2018). The evidence of storage decline, captured by GRACE, is in contrast with the intensification of extreme precipitation and flood events reported by Tabari (2020). According to the authors, there is a clear connection between floods and extreme precipitation changes with water availability. This means that the intensification of flood events increases as water availability increases from dry to wet regions. For instance, the changes in seasonal variability of precipitation can lead to extended dry periods - droughts, and also concentrated precipitation over a relatively short period - floods, leading to operational difficulties in reservoir water management (Konapala et al., 2020; Pascale et al., 2015).

Yun et al. (2021) showed that the future dry hydrological extreme could be mitigated by reservoir regulation, although the lack of reservoir storage capacity can be a challenge to water management. Similarly, Brown et al. (2019) reported that additions to reservoir storage and improvement in water use efficiency would be insufficient to avoid future shortages in the United States. Thus, adaptation measures that have been effective in the past may contribute, but will not be the answer to mitigate future events. To reduce the impact despite the increase in hazard, Kreibich et al. (2022) identified three success factors in the management of extreme events: (1) effective governance of risk and emergency management; (2) high investments in structural and non-structural measures; and (3) improved early warning and real-time control systems. In addition, it is essential to consider interactions between hazards, i.g. floods and droughts, to better design disaster risk reduction strategies and policies (Ward et al., 2020).

In the water supply sector, disaster risk reduction strategies are of paramount importance, since a disruption in the supply system means leaving communities, ecosystems, and many other sectors, including agriculture, energy, and manufacturing, in a vulnerable situation. For example, in the case of an extreme flood event, the water supply can be interrupted because of the flooded system, through the damage in the catchment, adduction and water distribution structures (Milograna et al., 2013). Similarly, an extreme drought event can directly impact water availability, ranging from loss of water supply to increased costs and reduced revenues. From the perspective of the water supply utility, these disruptions are difficult to remedy on a short-run basis as the operation prices cannot be easily modified (Baum et al., 2018). Therefore, there is a growing interest in developing new financial risk management strategies to reduce utilities and population vulnerabilities facing hydrological extreme events.

2.1.2 Climate change impacts on water quality

Global warming is unequivocal and has resulted in unprecedented changes on climate, including the quantity of water availability but also in water quality (IPCC 2021). More intense rainfall due to climate change (Tabari, 2020) would lead to greater rates of erosion, which would cause an increase in suspended solids (turbidity) in lakes and reservoirs. Also, the projected increase in precipitation intensity is expected to lead to a deterioration of water quality due to enhanced transport of pathogens and other dissolved pollutants (e.g., pesticides) to surface waters and groundwater (Bates et al., 2008).

Droughts are also increasing in frequency and severity in many regions of the world due to climate change (Tabari, 2020, IPCC 2021, 2022), which causes a reduction in runoff capture, impacting river flow and lake levels. Changes in the intensity and frequency of hydrological droughts also cause changes in water quality. Mosley (2015) reviewed several works around the world on the impacts of drought on water quality, and the author states that the decrease in volume during the drought usually leads to an increase in salinity due to the reduction in the dilution and concentration of water mass. In addition, the author points out that the concentration of nutrients and turbidity in rivers and streams decrease during droughts when there is no significant input of punctual and diffuse load. This is due to the increased influence of internal processes such as biological absorption of nutrients, denitrification and sedimentation. However, with the contribution of point sources, the concentration of such eutrophication-enhancing pollutants increases due to the lower dilution capacity in these events. Furthermore, during the dry season, there is an accumulation and storage of pollutants in the basin, with the mobilization of large loads of ions, nutrients and carbon at the beginning of the rainy season, which can cause oxygenation in the water body (Mosley, 2015).

In addition to the increase and severity of droughts and in air temperature, there is a growing concern that this changing environment affects the structure and composition of the phytoplankton community, including a greater prevalence and geographic spread of harmful algal blooms (HABs) (Wells et al., 2015). The occurrence of these events can produce toxic substances and taste and odour in the water (Mortazavi-Naeini et al., 2019), in addition to making the treatment difficult and expensive. According to Von Sperling (2014), changes in taste and odour in water are the leading cause of consumer complaints, who, when questioned about its reliability, may seek alternative sources of greater health risk.

As the efficiency of the treatment process is strongly dependent on the quality of raw water, the degradation of the water quality can increase the need for chemical or energy inputs or, even, it can lead to failures in the treatment process, requiring additional treatment (Thorne & Fenner, 2011). The high input of solids due to algal blooms or increased turbidity during the rainy season can cause partial shutdowns for maintenance due to operational difficulties in treating raw water (Maziotis et al., 2020; Mortazavi-Naeini et al., 2019; Thorne & Fenner, 2011). Water treatment process failures can undermine consumer confidence in the safety and reliability of the water supply (Raseman et al., 2017), in addition to generating economic losses to supply companies due to increased costs of treating raw water.

2.2 Socioeconomic drivers impacting water supply

Inevitably, global water demand is growing at a rate of 1% per year, and it will continue to do so in the coming decades (WWAP, 2018). The world population of 7.43 billion people had an annual water demand for all users of 4,600 km³ in 2016, and population growth will increase this figure by 20% to 30% in 2050, reaching an annual demand of 5,500 to 6,000 km³ (Burek et al., 2016). The river basin's water management challenges exceed their limit as well, contributing to clear inconsistencies between supply and demand due to climatic changes (Xiang et al., 2021).

With the growing concern for global water, energy and food security, a detailed exploration of the interconnections between them has gotten a lot of attention in recent years (Dai et al., 2018; Lee et al., 2017; Shu et al., 2021). Nonetheless, to reach the necessary synergy of both aspects, society has faced challenges involving the possible roads to take and the impacts generated for choosing determinate pathways of development for the future.

In order to meet the world's future sustainability needs, it is essential to develop a deeper understanding of the socioeconomic mechanisms behind water use trends to target the most-effective strategies (Soligno et al., 2019). According to Cazcarro et al. (2013), economic growth is influenced by changes in technologies, processes of input substitution, and changes in final demands. These technological, structural and demand factors also influence the patterns of resource consumption. Corroborating with these authors, Wang et al. (2014) highlighted how the change in water withdrawal is a consequence of factors associated with, and jointly influenced by population, GDP per capita, water use intensity, production structure, and consumption patterns. Furthermore, the authors point out that the growth of the population and the economy does not necessarily imply an overall increase in water withdrawals, but is linked to the behavior of the consumption. In this sense, the impact of socioeconomic alterations can imply a higher consumption and demand of water, even if the population growth is not high.

The crescent concern about the water supply has faced not only the problems with hydrological processes but also the intended and/or unintended consequences of long-term changes in social norms and values, ideology or political systems, which are not typically anticipated or accounted for in coping with water-related issues (Di Baldassarre et al., 2019). To put these aspects docket, sociohydrology perspective has become a key for adaptation to water scarcity, through the interactions of water consumption for food, energy and drinking water supply, pollution or freshwater resources, policies, markets and technology (Sivapalan et al., 2012). According to Sivapalan et al. (2011), under the sociohydrology principles, humans and their actions are considered part and parcel of water cycle dynamics, and the aim is to predict the dynamics of both. That approach could permit a better assessment of how the water distribution can be improved to meet multiple purposes, associated with effective structural and structuring policies, assisting in reducing water waste and improving water security.

2.3 Risk management options for water supply business interruptions

As previously stated, the occurrence of droughts, floods, and pollution extremes, which are frequently exacerbated by climate change and modulated by socioeconomic pathways, often causes disruption or unexpected increases in utility expenses. In this section, we will go over the mechanisms that utilities use to protect themselves from these events. Table 1 depicts a series of global cases to demonstrate the hazards, damages, and mechanisms by which utilities respond to them.

As shown in Table 1, despite acting through different mechanisms, the three types of hazards, when combined or isolated, are capable of disrupting the utility business by causing water service interruption, increasing costs in the treatment and maintenance of hydric infrastructure, and causing interruption to water-related business.

In the short term, water utilities' financial structures are based on approximately 80-95% fixed costs, with much of this (up to 50%) destined for debt service payments on infrastructure, and approximately 80-90% of the revenue comes from volumetric water sales (Hughes et al., 2014). Prices are set in such a way that revenues are expected to equal costs at the end of each budgeting period, which is typically annual (Hughes et al., 2014). Water offers fall during droughts, unbalancing revenue and exposing utilities to financial risk. Expanding and/or maintaining large supply capacities is one way to deal with this issue; however, the high cost and difficult regulatory approval processes associated with this measure (Scudder, 2012) force water utilities to frequently rely on conservation strategies to hedge drought, such as drought surcharges (Zeff & Characklis, 2013), as seen in the majority of the drought cases exposed in Table 1.

Droughts can last for months or years, putting serious constraints on the company's operations that can affect user’s needs. Low-frequency flood events, on the other hand, even if they last only a day or a few days, can cause damages to utilities due to equipment loss, additional operational costs, and welfare damages to consumers who experience disruption or loss of services, causing the utility to spend more on and after these events. As illustrated by the Minnesota case in Table 1, following these events, utilities respond by purchasing new equipment or infrastructure, increasing the amount destined for debt service payments on infrastructure in the face of a frequently constrained budget. Similarly, when there is a drought, the raw water quality can degrade due to reduced dilution in the source or by the need to abstract in low water levels, as is the case of the São Paulo Metropolitan Region (Table 1), increasing treatment costs and the frequency of maintenance outages. Furthermore, during wet periods, due to runoff and soil erosion, some treatment plants may face problems in treating water due to the high turbidity of the raw water (Thorne & Fenner, 2011; Maziotis et al., 2020). The degradation of water quality during weather extremes increases the utility's financial vulnerability during these events. Resizing treatment processes, diversifying water supply options, increasing plant design redundancy, changing long-term operations, developing effective plans to respond to extreme events, and improving water quality monitoring are some solutions to the raw water quality problem (Raseman et al. 2017). However, implementing some of these measures adds to the high cost and challenges regulatory approval.

Table 1 – Extreme events of flood, water pollution and drought in some locations around the world, damage associated with water supply and response measures taken.

Location of the incident	Period	Type of hazard	Description of hazard	Damage registered	Response measures taken	Reference
Guandu River Basin, Rio de Janeiro, Brazil	2020, 2021	Water quality degradation	High levels of dissolved total phosphorus, cyanobacteria, and enteric bacteria affecting the WTP causing eutrophication. Potable water driven from the river had high levels of 2-MIB/geosmin.	Series of water supply interruptions. Consumer dissatisfaction given to taste and odour of treated water, leading to the search for mineral water. A penalty of 1,06 million to the state water utility in 2020.	Use of activated charcoal in the treatment process. Use of Phoslock in lagoons. Opening the floodgates for flow with greater volume and speed, partially renewing the water in the lagoon.	Bacha et al., (2021); Rodrigues (2021).
São Paulo Metropolitan Region (Brazil)	2013-2015	Hydrological drought and associated water quality degradation	Reduced levels of flow in the reservoir systems due to reduced precipitation records.	Water utility massive revenue reduction profit of close to 60%. Direct and indirect economic losses in other sectors are dependent on the water supplied by the water utility.	Drought surcharges; advertising campaign; penalty and bonus tariff; pressure reduction; transfer for other reservoirs; reduced consumption; dead volume extraction; water treatment costs increase.	Guzmán et al., (2020); Marengo et al. (2015); Nobre et al. (2016); Souza et al. (2022); Taffarello et al. (2016).
Lake Erie Basin, Ohio, USA	2011, 2012, 2014	Water quality degradation (mainly) and Hydrological drought (some years)	Cyanobacterial bloom and hypoxia	Microcystins levels exceed drinking and recreational water guidance values. Water supply interruption for 500,000 users. Lake Erie's fishing and tourism industries were also affected.	Increase in treatment cost due to chemical acquisitions; water destined for other parts of the state diverted to the affected region; search for alternative water resources.	Dungjen & Patch (2022); Watson et al. (2016).

Cape Town, South Africa	2017-2018	Hydrological drought	Hydrologic drought due to reduced precipitation records	Reduced water revenue, losses in agricultural jobs and production and indirect costs such as a drop in tourism.	Drought surcharges; water use restrictions; search for alternative water resources; communication campaigns.	Muller (2018); Ziervogel (2019).
Metropolitan region of Barcelona, Spain	2007-2008	Hydrological drought	Hydrologic drought due to reduced precipitation records	US$ 511 million in economic costs of emergency measures; Direct and indirect economic losses in other sectors dependent on the water supplied by the water utility.	Water shipping; building pipes to distant rivers; water use restrictions; awareness campaigns; search for alternative water resources.	March et al. (2013); Martin-Ortega et al. (2012).
Minnesota, citys of Grand Forks, East Frand Forks, Fargo and Winnipeg, United States	1997	Flood	Fluvial floods that overcame dykes and reached the city	US$ 3.6 Billion in economic costs; more than 50,000 people had to be evacuated, and more than 11,000 houses and businesses were damaged; Water supply interrupted for five days.	Installation of pumps; protecting the water plant structure to avoid collapsing of walls and infrastructure, opening street valves to reduce the water pressure in the system; Increasing chlorination in the system to avoid contamination.	Bauer (2017); Thornley (1997).
Yorkshire Water, United Kingdom	2015-2016	Flood	Fluvial flooding caused by a series of storms.	US$22.3 million for water utilities in capital costs, operational costs, and welfare damages; some business interruptions were reported.	Pumping flood water.	Environment Agency (2018).

Water quality degradation is not always closely associated with weather extremes, as evidenced by the eutrophication events occurring in Rio de Janeiro and Lake Eirie, which are not associated with dilution capacity or runoff, as shown in Table 1. Both events, which occurred more than once, caused water and dependent services business interruption, users' dissatisfaction, and increased treatment costs. The former is caused by a lack of sewage treatment in the basin (Bacha, 2020), whereas the latter is caused primarily by diffuse agricultural pollution (Scavia et al., 2014), posing a greater challenge to water management. However, as Thornton et al. (2013) points out, the problem of nutrient enrichment was thought to have been solved by municipal wastewater treatment and storm water management, yet the eutrophication issue not only persists but is worsening in lakes and reservoirs. The climate change factor (Wells et al., 2015) and the unique characteristics of each ecosystem (Thornton et al., 2013) require acting not only to determine the cause of nutrient enrichment (which can be varied or uncertain), but also to mitigate the problem, such as financially compensating the water resource user.

During droughts, without enough water reserves to sell in a way that revenue and costs can be balanced, water utilities are often forced to buy water from other sources, such as neighbouring regions or drilling into aquifers, which are costly alternatives due to the source of the supply and infrastructure needed to transport it (Polasek, 2014). In terms of financial measures, water utilities can take three basic actions, hybrid or individually, to hedge against unbalanced expenses and revenues during droughts: drought surcharges, contingency funds, and index insurance contracts (Zeff & Characklis, 2013). Utilities may raise volumetric water prices to compensate for lost revenue and encourage users to conserve. Surcharges, on the other hand, are unpopular with users and thus politically difficult. The water company can self-insure against loss by making regular contributions to a contingency fund. However, given the challenges in drought variability, Zeff & Characklis (2013) believe that a high-liquidity fund large enough to hedge against the effects of multiple droughts over several years or an extended multiyear drought would require periodic contributions far in excess of expected revenue losses. Furthermore, local politicians have access to contingency funds that they can use for other purposes (Polasek, 2014).

Index insurance contracts are a way of mitigating financial losses due to weather and hydrologic extremes in agricultural, irrigation, water supply and energy production sectors (Benso et al. 2022). The third-party financial insurance contract is an insurance mechanism for the water utility sector (Polasek, 2014) that is still poorly explored. When it comes to drought hedging, these contracts have outperformed conservation measures like self-insurance and surcharges during more severe droughts (Zeff & Characklis, 2013; Baum et al., 2018). Similarly, Guzmán et al (2020) found that efficiency and solvency coefficients showed improved performance during high-intensity and low-frequency drought events. Furthermore, Zeff & Characklis (2013) emphasize that conservation measures can be used in combination with index insurance to effectively hedge against water-related disasters.

In exchange for a periodic payment known as a premium, these financial contracts transfer a portion of the financial risk to a third party. This third party is a financial institution that is in charge of taking on risk for one or more utilities. Alternatively, a group of utilities could pool their resources to self-insure against similar risks (Baum et al. 2018). The premium paid for the insured to the third party is calculated by adding administrative costs, third-party returns and the opportunity cost of reserves to the expected losses forecasted during the contract term (Baum et al. 2018). The losses are calculated using a pre-agreed value of an index, which must have a close relationship with the actual losses. As previously stated, index insurance is a risk management tool that has recently been studied by water utilities to hedge against drought. However, to the best of our knowledge, the insurance schemes proposed in the literature up to this point are only applicable to this type of risk. For water utilities, financial losses in terms of water quality and flood damage to water infrastructure, neither third-party financial contracts nor other elaborated financial risk transfer mechanisms are proposed or investigated.

3 Index insurance applied to water utilities

In this section, we discussed how index insurance is capable of enhancing user's resilience. In addition, we discussed the potential applications of index insurance for water infrastructure. We then propose a general index insurance framework for risk mitigation in the water infrastructure sector. Finally, some shortcomings in index insurance design and implementation are identified.

3.1 Index insurance as a mitigation tool

Given the uncertainties associated with both changes in climate extremes and socioeconomic choices to address the problem of water shortages and water security, as well as the definition of how these uncertain factors affect water supply, water infrastructure remains a risk. This residual risk is sometimes insurmountable with preventive measures, necessitating financial compensation to mitigate the damage. Indexed insurance is intended to be a tool for mitigating the vulnerability associated with the impacts of supply interruption or significant financial losses caused by extreme hydrometeorological events. Such a tool should ultimately aim to ensure water supply and increase population resilience in the face of uncertain scenarios. Therefore, the water consumer must be the final insured of such a benefit, which is directly applied to the intermediary insured, which consists of supply companies.

Given the supply companies' tight budgets, this mitigation can be translated into economic compensation for the economic losses suffered by the companies during extreme events from payouts (Baum et al., 2018). Guzmán et al. (2020) defend this form of mitigation as a way to protect the companies' business, and thus, the supply service. However, the payout can also be used to compensate the end user of water resources in addition to covering economic deficits or operating expenses of companies. This measure can be implemented in two ways: from the reduction of water tariffs; or by direct compensation to customers where the water company is responsible for interruptions in the water supply, as is the case of England and Wales. This measure constitutes a direct incentive for water companies to seek the reduction of unplanned interruptions in water supply, thereby improving service quality (Maziotis et al. 2020).

It is important to emphasize that, as a mitigation measure, the insurance schemes can work along with others to prevent the effects of extreme events on the water supply. Such measures comprehend, for instance, online monitoring of water quality, exploration of alternative sources of supply, resizing of treatment processes, diversification of water supply options, increased redundancy of the plant design, change in long-term operation and development of effective extreme event response plans can be implemented to achieve this (Raseman et al. 2017). Additionally, measures aimed at producing water based on ecosystem-based adaptation – which consists of taking advantage of biodiversity and ecosystem services to assist populations in adapting to the adverse effects of climate change – and its valuation based on payments for ecosystem services have been studied as water production solutions (Taffarello et al., 2017, 2018). For instance, Navarro et al. (2022) propose a risk management framework integrating insurance mechanisms with nature-based solutions to reduce the vulnerability of urban centres, allowing insurance coverage to be reduced as the population is less exposed. Furthermore, the authors emphasize the importance of using other non-structural measures such as institutional-level measures, sustainability policies, awareness of the risks and potential damages of extreme events, and multidimensional indicators, in addition to insurance Such measures raise awareness, which encourages people to adapt and pay for insurance, increasing the economic resources available for adaptation.

The proposal of this management instrument is not intended to be a diversion from the lack of measures aimed at the proper disposal of sewage and solid waste or to discourage the modernization of water infrastructure. As a result, the risk transfer model based on insurance has the potential to act in accordance with national and international sanitation and water security plans.

3.2 Index insurance structure

An insurance scheme is divided into product development (which includes risk assessment, premium calculation, portfolio analysis, and profitability monitoring); analysis of sales, customers, marketing and price sensitivity; complaints and fraud detection services; finance and controllership (which involves modelling financial risks, reinsurance and solvency) (Grize et al., 2020). Insurance products are classified into two broad categories: conventional insurance, in which premiums are calculated based on a series of actual losses suffered by the insured, and indexed insurance, or indexed climate insurance, in which premiums are frequently calculated based on a probabilistically estimated climate indicator. Indexed insurance has the advantage of reducing administrative costs, adverse selection issues, and moral hazard.

The methodology employed by the index insurance industry to produce probabilistic estimates related to the risk of natural catastrophes is based on a concept known as catastrophe models (or "CAT" models), which connects stochastic models with physically based models. Among the models inspired by the CAT methodology, the Hydrological Risk Transfer Model developed by the Department of Hydraulics and Sanitation of the University of São Paulo, called MTRH-SHS, which is a simulator of insurance funds for studying flood and drought hydrological risks from an economic point of view (Mohor & Mendiondo, 2017). The model is set up to define the insurance premium, determined by the risk of current or future extreme events and the ability to pay the premium. Thus, the MTRH-SHS has a methodology focused on the product development stage, specifically on risk assessment and premium calculation, as well as the solvency of the funds.

The MTRH-SHS structure is divided between the hazards, vulnerability and financial modules (Righetto et al., 2007; Mohor & Mendiondo 2017). The hazard module studies the variability of the index and simulates interest events. The vulnerability module calculates the expected damage related to the magnitude of modelled events in the previous module, the so-called damage curve. Lastly, the financial module transforms the associated damage with a produced event, in the vulnerability module, into a loss estimative to be insured (Sampson et al., 2014).

The MTRH-SHS was first proposed and applied by Righetto et al. (2007) to cover losses from flooding in an experimental basin. Losses were calculated from a relationship with the return time using extreme event simulation scenarios. According to Righetto et al. (2007) the methodology allows for the integration of insurance models with warning systems in basins.

Graciosa (2010) used hydraulic-hydrological modelling to assess the feasibility of implementing flood insurance in an urban hydrological basin. Laurentis (2012) coupled regional climate models, hydrological models and the MTRH-SHS as an adaptation strategy for several sectors affected by water scarcity in Brazilian watersheds due to the effects of climate change, land use, and occupation. Mohor & Mendiondo (2017) proposed a conversion of the value of insured premiums to a ratio of GDP, in addition to a simulation of the MTRH-SHS multi-sector insurance fund for droughts, because the adoption of such insurance-based indicators can improve the risk perception, encourage its mitigation and translate the potential water deficit into more tangible value for managers and policymakers. Guzmán et al. (2020) estimated the potential economic impacts of a water supply service interruption due to hydrological drought and proposed a mitigation strategy based on an insurance model aimed at protecting the sector's capital. The authors used climatic projections (represented by climate change scenarios), anthropogenic (represented by changes in water demand), and economic factors (considering the company's tariff strategy) as impacting agents on the value of the optimal policy in their model. Benso et al. (2022) proposed adapting the MTRH-SHS structure into a general framework from a non-stationary perspective. This vision includes the investigation of the hazard's non-stationarity (as explained by the index) in terms of severity and frequency, as well as the threshold, which, in turn, indicates a change in vulnerability, or susceptibility, of the individual or society over time.

3.3 Conceptual framework for water supply sector

At this stage of the paper, a general framework for adapting the MTRH-SHS to ensure supply companies in a multi-hazard and multi-driver context is proposed. This framework complements the model proposed by Guzmán et al. (2020), which, despite taking into account economic, climate, and anthropogenic drivers, did not take into account the multi-threat nature of shortage risks, and adapts the generalist framework proposed by Benso et al. (2020) to the supply sector. Figure 1A depicts the various classifications of indexed insurance for the supply sector based on the hazards and cases previously discussed in this work. Figure 1B depicts where, in the water supply chain, insurance can be used to protect water infrastructure.

A

	Water quality	Flood	Drought
Water quality	Insurance for water quality pollution (1)	-	-
Flood	-	Insurance for flood (2)	-
Drought	Insurance for drought and its associated water quality degradation (3)	-	Insurance for droughts (4)

B

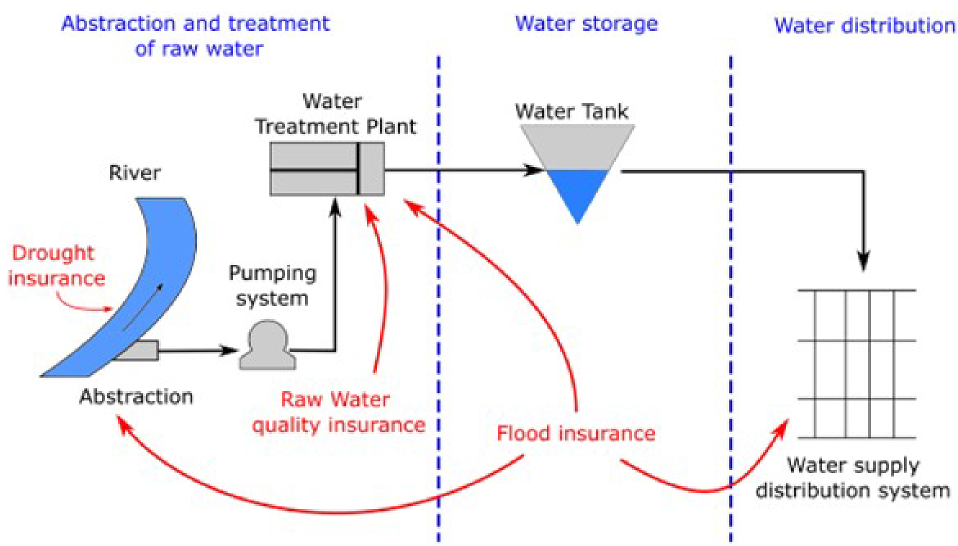

Figure 1 – Types of index insurance schemes based on different hazards (A) and where they can act in the water supply sector (B).

First, using the MTRH-SHS general methodology, the indexed insurance model can be adapted for the six types of hazard combinations listed in Figure 1A. The demand for one or more types of insurance schemes is determined by the disaster(s) that the supply company intends to ensure, given the history of service interruptions or difficulties in the face of extreme hydrological events. Four types of insurance can be outlined based on some global records of interruption or increase in expenses in the face of hydrological and pollution extremes (Table 1), as well as the relationship between quantity and quality of water:

- Type 1: Insurance for supply companies in which water treatment is frequently compromised (with an excessive increase in inputs or the need for additional treatment) due to the degradation of surface water quality, but there is no explicit relationship with hydrological extremes.
- Type 2: Flood insurance for supply companies whose collection, adduction, and distribution systems are entirely or partially located in a flood zone.

- Type 3: Insurance for supply companies where abstraction occurs in drought-affected watersheds, as well as the associated quality degradation during droughts (due to reduced dilution capacity).
- Type 4: Insurance for companies that extract water from a surface source that experiences periodic water scarcity.

Following the selection of the insurance scheme(s) based on the hazard combination in a given study area, after choosing the insurance scheme(s) according to the hazard combination, given study area, the next step in designing the insurance model is the selection of the index (Figure 2). The index must be composed of one or more variables that represent the behaviour of the hazard(s) in question. According to Baum et al. (2018) an effective index must be transparent, publicly available, easy to manipulate and well correlated with the series of losses. According to Chen et al. (2019) the precise selection of the index reduces the base risk (disagreement between the value of the premium and the losses), which increases the acceptability of insurance because the uninsured risk can be reduced. The authors point out that the precise choice of the index decreases the base risk (non-agreement between the value of the premium and the losses), which increases the acceptability of insurance since the uninsured risk can be reduced.

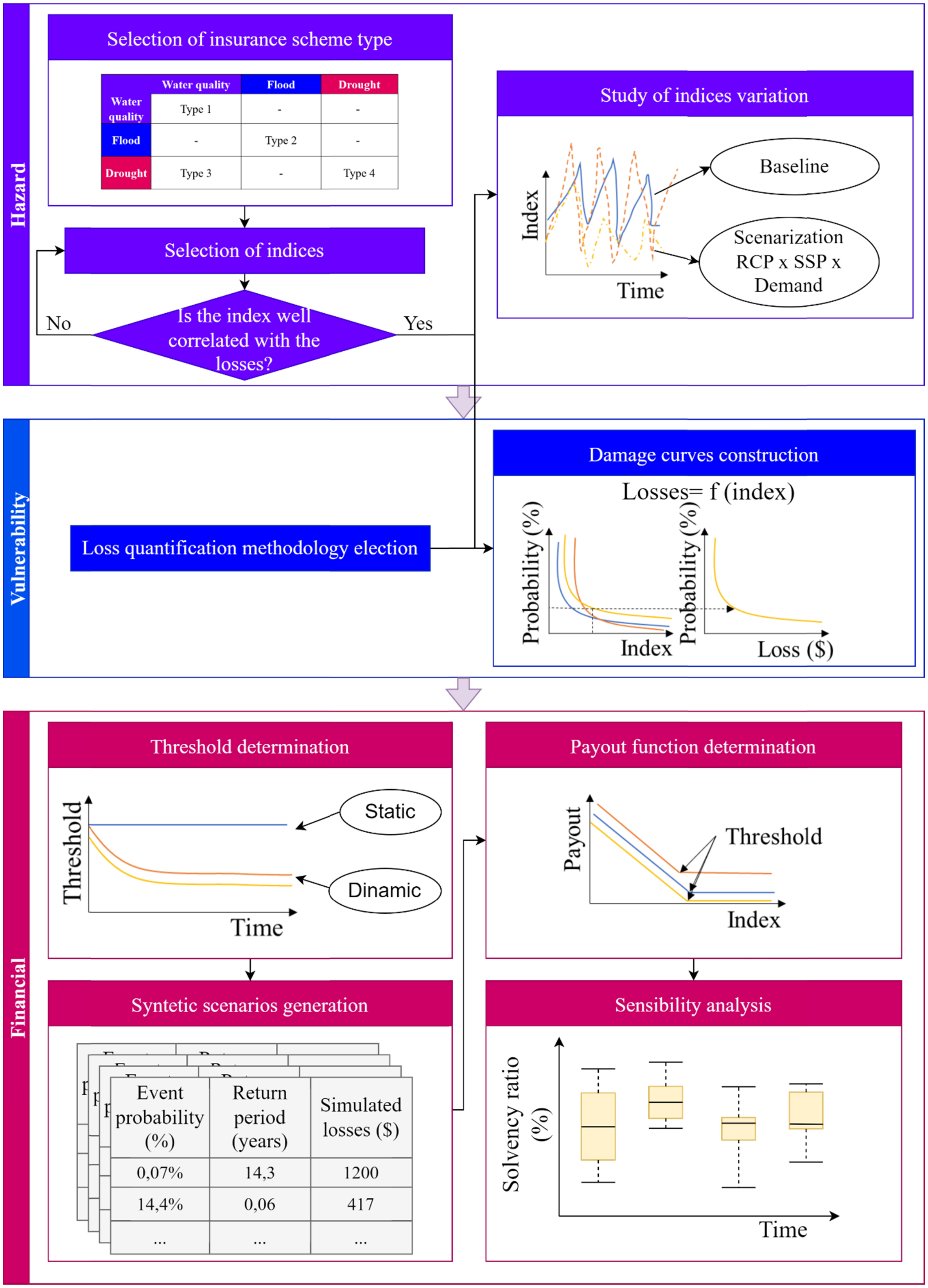

Figure 2 - MTRH-SHS general structure to water utilities.

Baum et al. (2018) investigated the degree of generalization of the index as another important factor in index selection. The authors point out that, while tailored indices (developed for individual circumstances) generally reduce moral hazard, they hinder the transparency, availability, and ease of contract development, therefore, encouraging the use of more general indices, such as streamflow and precipitation-based indices, to characterize droughts. Among the works that use generalist indices for low flow, Mohor & Mendiondo (2017) considered the minimum flow of 7 consecutive days indexed by the return period to represent drought in various sectors. Guzmán et al. (2020) used the duration of droughts and event return period as an indexing variable for insurance for the supply sector. Zeff & Characklis (2013) used reservoir storage level records for the supply sector as an example of tailored indices for drought. According to Baum et al. (2018), an index based on reservoir level can be easily influenced by company operations, making it vulnerable to inducing moral hazard problems.

As far as we are aware, no work has yet proposed an insurance model to compensate for damages resulting from pollution extremes, whether associated or not with hydrological extremes (Types 1, and 3). Thus, given recurring cases in several basins worldwide of increased turbidity or suspended solids due to increased surface runoff (Bates et al., 2008) in periods of high flow, which can cause frequent outages for maintenance, or an increase in the concentration of nutrients in reservoirs during dry periods under the presence of punctual affluent loads, which facilitates the proliferation of algae, or even, the need to capture at low levels or the dead volume consisting of water of lower quality during droughts, which increases treatment costs of water (Tafarello et al., 2016). We propose that future works explore the relationship between these indices and increases in company expenses or the frequency of stoppages. In cases of choosing the index to represent flood impacts, indices to characterize damage to urban infrastructure in general (Aerts & Botzen, 2011) or water level in treatment plants during floods (Milograna et al., 2013) have already been reported in the literature.

In the study of the index's variability resulting from the generation of stochastic series, two basic approaches can be reported: one based on the historical series, known as baseline, and another including scenarios considering uncertainty drivers such as socioeconomic scenarios, climate change and demand change (multi drivers). Long-term global scenarios have played a key role in climate change analysis. Scenarios of global development focus on the uncertainty in future societal conditions to explore mitigation, adaptation and residual climate impacts in a consistent framework (O'Neill et al., 2017). The long-term demographic and economic projections depict a wide uncertainty range consistent with the scenario literature. Trying to surpass the complexity and understand how the trajectories of the climate and human activities components will follow, for the elaboration of the energy, land-use and emissions trajectories scenarios, it is commonly used a combination of different Socio-economic Pathways (SSPs) and the Representative Concentration Pathways (RCPs) (IPCC, 2022; O'Neill et al., 2017; Riahi et al., 2017). Each SSP integrates population projections and economic growth, as technological and geopolitical trends. Through five different narratives (sustainability, regional rivalry, inequality, fossil-fueled development and middle of the road), they allow demonstrating of how different socioeconomic aspects impact climate change and permit to analyze and create strategies to minimize the negative characteristics generated by suppressions in water availability for the present and especially for the future, exploring projections, implications and solutions (O'Neill et al., 2017) to face the crescent problem of water supply.

In this way, such drivers impact water availability in time and space. Therefore, it is emphasized that, when estimating policies, the influence of multidrivers in the calculation of optimal premiums is critical, because contract negotiation without studying the index's stationarity may allow the insurer to transfer an uninsured risk (Zeff & Characklis, 2013), and cause adverse selection problems, which include a lack of information about the disaster's impact (Zhu, 2017). Due to a lack of information about the disaster's impact on multi-drivers, insurers may unintentionally assess the risks following a catastrophic event, resulting in reduced insurance availability and affordability (Cremades et al., 2018).

The methodologies for quantifying financial losses due to drought for insurance models tested thus far consist of the direct consideration of drought impacts on revenue, given the sector's high susceptibility to volumetric sales, affected by the imposition of conservation measures (Polasek, 2014; Baum et al. 2018; Baum & Characklis, 2020), or in the direct relationship of tariff adjustment (a conservation measure) with drought intensity (Guzmán et al. 2020). In general, methodologies for quantifying damage from droughts, floods and water quality degradation are currently scarce, particularly in developed countries with poorly monitored urban basins (Fava et al., 2022). In this regard, it is critical to emphasize the importance of coordinating efforts to collect and make available hydrological data, as well as transparency in operating records, consumption of inputs in water treatment and accuracy in reporting failures due to outages in the treatment systems caused by extreme events. With the series of losses, a relationship between the index's behaviour and the losses is developed, known as the damage curve.

The financial module is divided into three steps: generating equiprobable series of extreme events, optimizing premium calculation, and performing sensitivity analysis for different insurance coverages. Thus, the payout function is defined and optimized in this module based on the generation of equiprobable scenarios. When defining the degree of coverage, the threshold (value from which insurance is triggered) can exhibit either stationary or non-stationary behaviour (Benso et al., 2022). The threshold in stationary behaviour is unique for the entire duration of the contract; this is the typical methodology used for existing indexed insurance. Benso et al. (2022) introduced the concept of dynamic threshold in a non-stationary system that is influenced by system resilience. Resilience is defined as “the ability of a system, community or society exposed to hazards to resist, absorb, accommodate, adapt to, transform and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions through risk management” (UNDRR, 2015).

Similarly, this prerogative can be adapted to the supply sector from the perspective that resilience is altered due to the consequences of socioeconomic choices such as changes in land use, changes in demand, degree of development and implementation of adaptation measures and mitigation of climate change, etc. All of these factors influence water demand and availability. Thus, the recurrence of an event of a certain duration, magnitude, or frequency can have a greater or lesser impact on water supply over time, depending on the degree of development, implementation, and maintenance of resilience measures. These changes in the water supply affect the vulnerability of the supply companies' businesses while also necessitating the need to adjust the threshold over time. However, defining the threshold's behaviour as a function of time can be difficult. We emphasize the importance of additional research into models and uncertainties in determining the threshold function over time.

3.4 Gaps and challenges in index insurance design and implementation for water supply

Many studies in the design of insurance models are still needed for the water supply sector. Future research in the hazard selection stage should better investigate the relationship between droughts, floods, and pollution extremes and their interaction and implications for supply financial losses. Furthermore, more studies should investigate the relationship between indices that depict water pollution and increased treatment costs, as in (Cunha et al., 2016), as well as increased frequency of outages, which are ways of measuring financial losses within an insurance framework. Damage quantification methodologies should be better studied and sedimented in the characterization of losses, concurrently with the collection and continuous monitoring of damage series. After these aspects have been improved, it is possible to analyze the performance of insurance funds in honoring the policies.

While promising, index insurance uptake is still considered to be low (Clement et al., 2018) .According to Chen et al. (2019), the low demand is attributed to the high base risk, which constitutes a mismatch between the indices and the losses occurrence. Furthermore, due to the uncertainties of the index choosing and the losses modeling, the unsecured residual risk can be high, mainly for the supply sector, in which risk transfer contracts is a study field in progress, making way for base risk characterization and control studies. Nonetheless, the level of basis risks is more important from the insured's perspective. The insurer is concerned with the predictability of payouts and the size of reserves to ensure solvency. In this way, the study of risk pooling effectiveness is substantial (Baum et al., 2018). Risk pooling comprehends a set of individuals with similar risk, but low autocorrelated, contributing to a unique fund drawn down when part of the individuals experiences a loss. The risk must be independent in a way that only a low number of individuals experience a loss at the same time. So, the premium can be closer to the level of expected payouts, reducing the need for the insurer to keep large reserves and lowering opportunity costs (Baum et al., 2018; Baum & Characklis, 2020). To that end, insurers will need to develop and test the potential of index insurance instruments pooled across multihazard contexts of drought, flood, and water pollution, as well as multidriver contexts of climate change and socioeconomic pathways. Also, risk pooling must aggregate studies of the suitable length of the water utilities in terms of the served user, given that covering expenses to water utilities that supply extensive and close regions could have a high cost.

Aside from modelling studies on indexed insurance, studies that examine companies' maximum willingness to pay for service reliability and insurance, as well as their perception of the risk of water scarcity due to hydrological and pollution extremes, represent a significant gap. Such studies could provide a clearer picture of the demand for and acceptance of indexed insurance for water resource users, in addition to assisting in the development of insurance models.

4 Conclusion and final considerations

Given the uncertainties associated with both climate extremes and socioeconomic choices to deal with the problem of water shortages and water security, as well as the definition of how these uncertain factors affect water supply, a residual risk remains in the water infrastructure, which is not capable of being eradicated with preventive measures, requiring financial compensation to mitigate the damage. Indexed insurance, a relatively recently researched risk transfer methodology for the supply sector, is one of several financial tools that can help supply companies reduce risk and maintain financial stability. In the face of the supply companies' tight budgets, this mitigation can be translated into economic compensation for the economic losses suffered by the companies during extreme events as a way to protect the companies' business, and, thus, the supply service. The payout can also be used to compensate the end user of water resources in addition to covering economic deficits or operating expenses of companies. This measure constitutes a direct incentive for water companies to seek the reduction of unplanned interruptions in the water supply.

However, given the complex vulnerability to different hazards related to the quantity and quality of raw water to which the operation of supply companies is often exposed, in addition to the drivers of uncertainty affecting water availability, improving the application of risk transfer models is still necessary in order to incorporate such multiple risks and uncertainties. Many gaps and limitations in the design and implementation of water infrastructure insurance remain, including improved characterization of the relationship between droughts, floods, and pollution extremes and their implications in financial losses for supply; better research and development of damage quantification methodologies, primarily related to water quality degradation; and policyholder perception of the risk of shortages and willingness to pay for the insurance.

The proposal of this management instrument is not intended to be a diversion from the lack of measures aimed at the proper disposal of sewage and solid waste or to discourage the modernization of water infrastructure. As a result, the risk transfer model based on the index insurance has the potential to act, along with other mitigation tools, in accordance with national and international sanitation and water security plans.

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Competing Interests

The authors declare no conflict of interest.

Availability statement

The data presented in this study are available in the article itself and references cited.

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