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Discussion Paper on Risks to Water Resources

Resource and Environment Working Group

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Risks to Water Resources

This discussion paper was prepared by the Resource and Environment Working Group (REWG) of the International Actuarial Association (IAA).

It was primarily an effort of a subgroup of the REWG, the members of which are Stephen Lowe, Rade Musulin and Dale Hall. Constructive comments were made by other members of the REWG and the Scientific Committee.

This paper has been approved for publication by the REWG and the Scientific Committee of the IAA. The IAA is the worldwide association of professional actuarial associations, with several special interest sections and working groups for individual actuaries. The IAA exists to encourage the development of a global profession, acknowledged as technically competent and professionally reliable, which will ensure that the public interest is served.

The role of the REWG is to identify issues related to resources and the environment of interest to actuaries and to which the actuarial profession, at an individual or national level, can make a useful contribution in the public interest.

The views expressed in this paper do not represent those of the IAA, nor those of the entire REWG.

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Executive Summary

Water resources are critical for human survival. Since humans cannot survive for more than a day or two without clean water to drink, even short-term disruptions in the supply of water can have potentially devastating consequences, including adverse impacts on financial security systems.

Water resources are at risk from a variety of sources. We need to understand these risks so that they can be managed, through both prevention efforts before the risk events happen and mitigation efforts after the events happen. Risk management requires thoughtful prioritization as expenditures for prevention and mitigation are not limitless.

The main purpose of this paper is to start a conversation on water resource risk, first among actuaries and then within the broader scientific and public policy communities. We believe that actuaries need to be informed about broader societal issues such as this one, as water resource risks affect a wide range of perils commonly insured. And, once informed, actuaries will be in a better position to make a positive contribution to policy development.

The paper examines the risks to *water resource systems*, which include both natural and human elements. There is a natural hydrology to water, as it flows through rivers into lakes and oceans, permeates the soil to contribute to aquifers, and evaporates and condenses in the atmosphere. There are human activities that affect the natural hydrology, and human systems that overlay it, operating to collect and distribute water to populations.

The paper illustrates these water resource risks by considering three representative systems: those in New York City, Mexico City and India. A generalized *risk register* is developed that identifies and classifies the risks that all such systems face. Each of the three representative systems is then assessed using the risk register as a starting point. The assessments look at each risk along four dimensions: *Likelihood*, *Scope of Impact*, *Extent of Impact* and *Controllability*. These dimensions are important to prioritizing prevention and mitigation activities. In each case we touch upon the risk management activities that are already underway to protect the users of the system.

The paper employs what we believe to be best-practice actuarial risk management techniques, applied in a context outside the traditional actuarial domain. It may therefore serve as a useful educational tool, and a showcase for the profession's risk management capabilities.

While the three cases are far from comprehensive, they suggest quite strongly that we are facing a looming water crisis, of existential proportions, in some parts of the world. Water supplies in some regions will simply run out, as they may in Mexico City. In other regions the supply may remain, but the water will become undrinkable. In still other regions, like New York City, water supply is not a significant issue, unless there is a successful attack that damages and disrupts the system. The disparity between well-functioning systems and systems that are struggling is likely to increase. The India case is special (but not unique) because India's heavy use of antibiotics to treat water-borne illness, rather than purifying the water, has potential ramifications beyond water supplies.

Finally, we consider the implications of water resource risk on the various private and public financial security systems that actuaries support, including life, health, property and agriculture.

1. Introduction

Water resources are critical for human survival. We need clean water to drink, to cook with and to bathe in; and we need semi-clean water to grow crops and provide food for livestock. Water is also necessary in the production of many essential goods and services. A special case is the use of hydropower to generate electricity. The World Health Organization has published the chart below that shows a hierarchy of water needs. It estimates that the basic needs of each person require between 50 and 100 litres of water a day (between 13 and 26 U.S. gallons).

Of course, the upper portion of the chart focuses on basic needs; the water required to support food production and manufacturing is several multiples larger than that needed for basic human needs.

Since humans cannot survive for more than a day or two without clean water to drink, even short-term disruptions in the supply of water can have potentially devastating consequences. We have seen many instances where a shortage of water caused human suffering on a large scale. It can also lead to increased levels of political tensions; in the extreme, shortages could lead to armed conflicts between states, as they seek to gain control over water in short supply.

Chart 1: Hierarchy of Water Needs and Estimated Requirements

Source: How Much Water is Needed in Emergencies? World Health Organization

Water resources are at risk from a variety of sources. We need to understand these risks so that they can be managed, through both prevention efforts before the risk events happen and mitigation efforts after the events happen. Prevention and mitigation efforts entail costs, which must be compared to the benefits (reduction in adverse impacts) to sensibly prioritize expenditures.

Actuaries are accustomed to using risk management processes to evaluate, understand and prioritize risks; and ultimately to manage them. Without pre-planned management, catastrophes that do eventuate often do more damage, and can be destructive to the institutions and fabric of society.

The main purpose of this paper is to start a conversation on water resource risk, first among actuaries and then within the broader scientific and public policy communities. We believe that actuaries need to be informed about broader societal issues such as this one, as water resource risks affect a wide range of perils commonly insured. And, once informed, actuaries will be in a better position to make a positive contribution to policy development.

Some water risks arise from, or are being exacerbated by, climate change. However, environmental risk management also covers risk management not related to climate change, and this paper falls in that latter category.

This paper is meant to be an introduction to the subject of water resource risk. We would expect that further work in this area would entail input from and collaboration with subject-matter experts in hydrology, engineering, security, etc. In particular, our risk assessments were made without the benefit of such expert input; that input might cause us to modify our assessments. Our three examples are also far from comprehensive.

Finally, we wanted to showcase some of the risk management techniques now in use by actuaries, and how they can be applied in the broader context of environmental risk; students of risk management may find the paper instructive.

On the Nature of Water Resources

Water is extremely dynamic; it operates within, and is fundamental to, the earth's ecological system. Water flows on top of the land in rivers and streams; it gathers in basins to create ponds and lakes. It percolates into the land, creating aquifers that flow underneath the land. Eventually these flows take the water into the seas. Within the seas, there are massive water conveyors (such as the Gulf Stream) that move and mix warmer and colder waters. The water evaporates from the seas into the atmosphere, and then precipitates back onto the land, with desalinization as a by-product benefit. The hydrology of the water system means that water resource risks can include downstream effects and create widespread impacts.

While the earth holds a vast amount of water, it is still globally a finite quantity. And, most of the water is in saline oceans that are not drinkable.

Human societies have overlaid their own hydrology systems on the natural hydrological cycle. The Romans, Aztecs, Chinese and other ancient civilizations-built dams to create additional water basins to stabilize supply; and aqueducts, canals and tunnels to move water from collection points to consumer locations. These efforts continue today. We build wells that draw water from the aquifers to meet the needs of people, agriculture and industry. And we drill into the earth to extract oil, gas and minerals; often injecting water into the ground as part of the extraction process.

In addition to man-made alterations to the hydrology, humans also alter the composition and purity of the water through our personal and industrial activities. The water may still flow in the same manner, but it may not be useful in the same way because it is unsafe to drink.

2. Applying a Risk Management Approach to Water Resource Risk

We will apply a risk management approach to gain a better understanding of water resource risk. We will start by identifying the sources of risks; initially, risk identification will be generic, applicable to all water resource systems. We will then move to specifics via several illustrative case studies relating to specific water supply systems. Risk identification will look at sources of risk, as well as risk events that reflect their manifestation.

After the risks are identified we will consider the impact of each risk event along several dimensions, including likelihood, scope and depth of impact, and controllability. These dimensions are important for sensible prioritization of prevention and mitigation efforts.

Finally, we will consider prevention and mitigation efforts in terms of their costs and benefits. Since resources are always limited, it is imperative that prevention and mitigation efforts be directed towards those risk events that are controllable, are more likely and/or have greater impact. This will be a high-level assessment only. It will be illustrative of the risk management approach that we are espousing.

3. Risk Identification: A Generalized Risk Register for Water Supply Risk

Our first step is to identify the risks to any given water supply. To start, we develop a generalized risk register applicable to all water supply systems. The results are shown in Table 1 below. The risks are classified into three broad categories:

1. *The water goes elsewhere; the supply becomes insufficient*. Here we identify risks to the supply of the source water itself. Since there is a fixed amount of hydrogen and oxygen on the earth, there is a relatively fixed supply of water globally. However, the pattern of rain and snowfall in a particular region could change, reducing the local supply.

   While most of the focus is on a reduction in supply, we include in this category abrupt increases in the demand for water in the region; demand could increase substantially due to changes in economic activity, or a supply problem in an adjacent region. Regardless of whether there is a decrease in supply or an increase in demand, there would be insufficient water collected to meet the needs of consumers.

   One example of this category would be the upstream diversion of a river by an unfriendly neighbouring state that needs the water for its own uses. Many rivers, such as the Nile, Mekong and Jordan, are shared by multiple countries. Conflicts over shared water are likely to be an increasing problem. This is also where climate change comes into play, as decreases in levels of rain or snowfall may diminish the available water in rivers and reservoirs.

2. *Water is there, but the water delivery system is disrupted in some significant way.* In this category we consider ways in which the existing water supply at the reservoirs cannot be delivered through the system to consumers. Water supply systems consist of a collection point where the water is gathered and a delivery system that moves the water from collection point to consumption point. Usually the collection point is a reservoir, lake or

river, but it could also include a desalinization plant or similar facility. Delivery systems include networks of aqueducts, tunnels and pipes; and pumping stations along the way. Dams can fail; aqueducts can be damaged.

Examples in this category are abundant. An earthquake could destroy aqueducts and other conduits, disrupting the water flow. This is a concern in San Francisco and every earthquake-prone area. Land subsidence could alter elevations, disrupting gravity-based water flows. A group seeking to disrupt the system could damage conduits, creating similar effects. Finally, a lack of maintenance and neglect could cause the delivery infrastructure to deteriorate to the point that it no longer functions properly.

Table 1: Generalized Risk Register for Water Resource Risk

Principal Risk	Type	Risk Event	Direct Impact	Following Impacts
Water goes elsewhere	Natural and human causes	Reservoirs are depleted due to hydrological changed caused by climate change, which causes rain and snow fall to decline in region, and evaporation to rise, leading to drought conditions.	Region becomes uninhabitable without potable water supply; alternative freshwater solutions (desalinization plants, etc.) take too long, cost too much	Property in region becomes worthless; people are forced to migrate elsewhere, without the financial means to do so; regional economy is disrupted while being relocated; morbidity and mortality rises; social and political unrest as migrants struggle with relocation
	Human causes	Failure of a neighboring region's water system necessitates sharing of water supply; new aqueducts are constructed to share one region's water with another region	Region suffers water shortages, and strict rationing becomes necessary; it takes years to fully address the shortage	Population, business and tourism all decline as region becomes "not the place to live, work and visit"; political unrest pits region against its neighbors
Water is there, but delivery system is disrupted	Natural causes	A significant earthquake or other major ground motion event causes aqueducts and pipes to break, causing shutdown of delivery system; land subsidence causes shifts in elevations, rendering gravity-based water flows inoperative	Region is without drinkable water supply while emergency repairs are undertaken; damage is significant, such that it takes months to bring the system back online	Region is forced to declare a "holiday", encouraging residents to go elsewhere temporarily while repairs are undertaken; federal program provides lost wages to those who cannot work; workers living outside affected area bring water to work with them every day; disruption to regional economy could be minor or significant
	Human causes	Terrorists use nuclear bomb or massive conventional explosive to destroy reservoir dams and aqueducts, rendering the delivery system inoperable	Region is without drinkable water supply while emergency repairs are undertaken; damage is massive, such that it takes roughly a year to bring the system back online	Property values in region decline significantly, rise in unaffected areas, as many residents leave and do not come back; infrastructure in region becomes unaffordable; infrastructure outside affected area is overwhelmed; morbidity and mortality rise; disruption to regional economy is significant, as workforce is disrupted

Principal Risk	Type	Risk Event	Direct Impact	Following Impacts
		Terrorists destroy underground water delivery pipes, leading to temporary shutdown of affected parts of system	Region is without drinkable water supply while emergency repairs are undertaken; damage is manageable, such that it takes only one month to bring the system back online	Region is forced to declare a "holiday", encouraging residents to do elsewhere temporarily while repairs are undertaken; federal program provides lost wages to those who cannot work; workers living outside affected area bring water to work with them every day; disruption to regional economy is minor
		Maintenance of system is inadequate, neglected system deteriorates, leading to widespread water leakage and ultimately a significant system failure	Region is without drinkable water supply whenever emergency repairs are required; damage is manageable but frequent, such that outages last a few days or perhaps a week	Region's water supply system is characterized as that of a "third-world country"; outages are frequent and public is outraged; residents and businesses move elsewhere; region enters permanent decline, as population, property values and social order declines
Water is there, but becomes undrinkable	Human causes	Terrorists poison the water, either in the reservoirs or in the aqueducts and pipelines, leading to emergency shutdown of system while water purification steps are undertaken	Region is without drinkable water supply for perhaps a week, while water purification is undertaken; prior to its identification a large number of people are sickened or die from drinking contaminated water	Lack of water for a week is a manageable program, assuming the public listens to officials and stops drinking the water; however, people are afraid to drink the water afterward dur to the significant loss of life; business and population declines; tourism takes a major hit
		Industrial or agricultural pollution contaminates aquifer, making water undrinkable	Water must be boiled or purified by other means by residents, while solution at the source is developed and implemented; crisis situation lasts perhaps for one month	Population, business and tourism all decline as region becomes "not the place to live, work and visit"; significant numbers of people are sickened because they do not take proper purification steps

3. *Water is there, but it isn't potable*. In this area we consider ways in which the water could become contaminated, by either human or natural activity. Contamination could be accidental, incidental or purposeful.

   The high levels of lead found at Love Canal in New York State is an example. Ironically, in some areas flooding can cause mixing between fresh water and sewage waste, rendering the water supply undrinkable for a period. Some are worried that fracking will lead to contamination of water tables.

In each of the broad areas we describe the risks, first by articulating a risk event or scenario that captures the essential manifestation of the risk. We then articulate the impacts that are likely to eventuate from the risk event. In specific situations the impacts may be greater or less than we have articulated.

A risk register such as the one in Table 1 is a useful risk management tool. Many organizations review theirs periodically, updating it to reflect newly emerged risks and adjusting impacts to reflect their current situation.

4. Risk Assessment

Classifying the Risk Impacts

An important step in assessing the risks is to classify them along four dimensions:

1. *Likelihood*. While many favour assigning probabilities to risk events, this can be problematic because there may be no experience on which to base the probabilities. For risk management purposes it is often sufficient to assign the likelihood qualitatively, along a spectrum from Imminent, to Probable, to Unlikely, to Very Unlikely, to Speculative.

2. *Scope of Impact*. Here we are referring to the geographic dimensions of the risk event. The spectrum in this case ranges from Local, to Regional, to Global. The impact from events might be local; for example, affecting a single city. The impact might be regional, affecting a significant part of a continent; for example, the entire Mediterranean. Finally, the impact might be global, in that it affects the entire world.

3. *Extent of Impact*. This classification captures the degree of harm to those in the affected area if the risk event happens. It ranges from Disruptive, to Endurable, to Crushing, to Existential. The risk might be significantly disruptive, creating significant inconvenience, but without serious damage to societal systems. Alternatively, it might cause some disruption to societal systems, lowering quality of life in some meaningful way, but still allow people to continue with their lives. A more significant event could be crushing, in the sense that societal systems would be significantly disrupted, preventing people from continuing to live where and how they did before the event. Lastly, the event could be existential, meaning a significant number of people would die.

4. *Controllability*. Some risk events will be beyond human control to prevent, and also beyond human control to mitigate when they do occur. (An extreme example would be a large meteor striking the earth, causing a global winter that renders the planet uninhabitable.) Other events may be beyond human control to prevent (at least with current technology) but may be susceptible to a meaningful level of mitigation. Here the spectrum runs from Preventable to Unpreventable and Mitigable to Unmitigable.

Risk assessment is more meaningfully performed in specific cases, rather at the generalized level. To carry the analysis forward we will consider several cases, the first being the water supply system for New York City.

Case 1: New York City Water Supply System

Overview of the New York City Water Supply System

New York City's water supply system is one of the most extensive municipal water systems in the world, relying on a combination of aqueducts, reservoirs and tunnels to meet the needs of metropolitan New York City's more than nine million residents and its many visitors.

The system consists of aqueducts, distribution pipes, reservoirs and water tunnels that channel drinking water from upstate New York to New York City and four upstate counties bordering on the city. A comprehensive raised-relief map of the system is on display at the Queens Museum of Art.

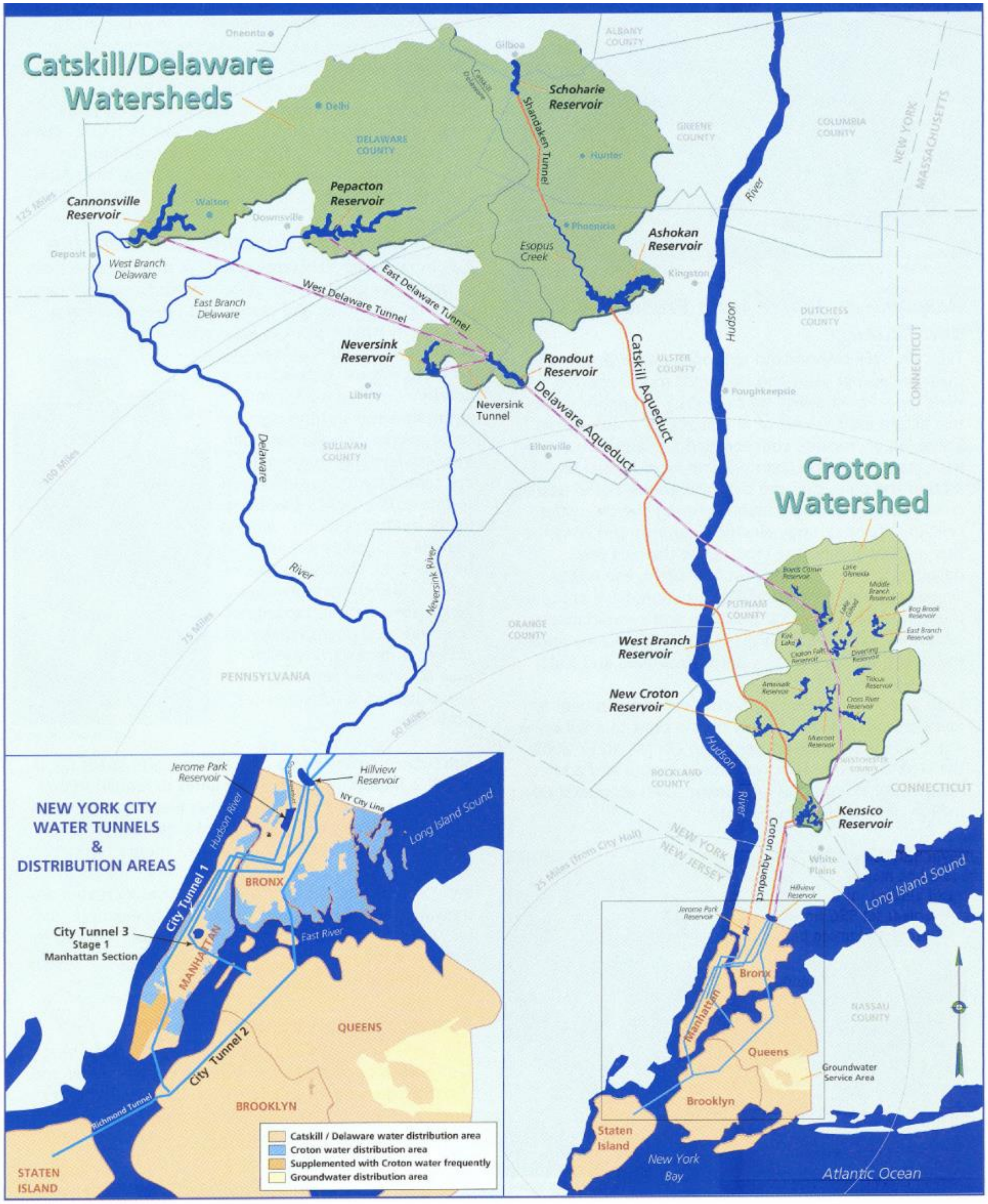
The water system has a storage capacity of 2.1 trillion litres (550 billion U.S. gallons); it provides over 4.6 billion litres (1.2 billion U.S. gallons) per day of drinking water to its customers. Water is delivered from upstate New York via three distinct aqueduct systems:

- The New Croton Aqueduct, completed in 1890, brings water from the New Croton Reservoir in Westchester and Putnam counties to the Jerome Park Reservoir in the Bronx; it supplies less than 10% of the system's overall water supply.
- The Catskill Aqueduct, completed in 1916, is significantly larger than New Croton and brings water from two reservoirs in the eastern Catskill Mountains; this aqueduct provides approximately 40% of the system's water supply.
- The Delaware Aqueduct, completed in 1945, taps upstream tributaries of the Delaware River in the western Catskill Mountains; this third aqueduct provides approximately 50% of the system's water supply.

The watershed for the latter two aqueducts extends to a combined 4,000 square kilometres (1,000,000 acres). Water from both aqueducts is stored first in the large Kensico Reservoir, about five kilometres (three miles) north of White Plains in Westchester County, and subsequently in the much smaller Hillview Reservoir in Yonkers, NY, just north of the city limits.

The water is monitored by robotic buoys that measure temperature as well as pH, nutrient and microbial levels in the two reservoirs. A computer system then analyzes the measurements and makes predictions for the water quality. In 2015, the buoys took 1.9 million measurements of the water in the reservoirs.

Chart 2: New York City's Water Supply System



Source: New York City Dept. of Environmental Protection;
www.dec.ny.gov/docs/water_pdf/nycsystem.pdf

From the Hillview Reservoir, water flows by gravity to three tunnels under New York City. Water rises again to the surface under natural pressure, through a number of shafts. The three tunnels are:

1. *New York City Water Tunnel No. 1*. Completed in 1917, Tunnel 1 runs from the Hillview Reservoir under the central Bronx, then under the Harlem River to Manhattan. It extends under Manhattan's West Side, Midtown and Lower East Side, then under the East River to Brooklyn, where it connects to Tunnel 2.

2. *New York City Water Tunnel No. 2*. Completed in 1935, Tunnel 2 runs from the Hillview Reservoir under the central Bronx, then under the East River to western Queens and western Brooklyn, where it connects to Tunnel 1 and the Richmond Tunnel to Staten Island. When completed, it was the longest large-diameter water tunnel in the world.

3. *New York City Water Tunnel No. 3*. Not yet completed, Tunnel 3 is the largest capital construction project in New York City's history. It also starts at Hillview Reservoir. Like Tunnel 1, it runs under the central Bronx, then under the Harlem River to Manhattan. It extends under Manhattan's West Side, crossing under Central Park to reach Fifth Avenue at 78th Street. From there it runs under the East River and Roosevelt Island into Queens. It will eventually continue on to Brooklyn.

The distribution system from these tunnels is made up of an extensive grid of water mains stretching approximately 10,900 kilometres (6,800 miles). As of 2015, it costs New York City US$140 million annually to maintain these water mains.

Risk Prevention and Mitigation Activities Relating to the New York Water Supply System

New York City engages in substantial risk prevention and mitigation activities to protect the public from water supply risks. This is in part because it is a wealthy city that can afford to spend on protective measures, in part because it is an established target in need of protection and in part because it is an important economic and financial centre that is vital to the U.S. national interest.

Risk prevention activities include the following:

- New York City has sought to restrict development throughout the system's watershed. It has purchased, or protected through conservation easements, over 525 square kilometres (130,000 acres) of land surrounding the system since 1997.

- Two-fifths of the watershed is owned by the New York City, state or local governments, or by private conservancies. The rest of the watershed is private property that is closely monitored for pollutants; development upon this land is restricted.

- The water supply is so critical to the city that a dedicated police force with more than 200 members works 24 hours a day to prevent illegal dumping and other misuses of the waterways.

Risk mitigation activities include the following:

- The construction of Tunnel No. 3 is intended to provide the city with a critical third connection to its upstate New York water supply system, allowing the city to close Tunnels No. 1 and No. 2 for repair for the first time in their history. The tunnel will eventually be more than 96 kilometres (60 miles) long. Construction on the tunnel began in 1970, and its first and second phases are completed. The latter opened in 2013. Completion of all phases is not expected until at least 2023. Prior to the construction of Tunnel 3, the system had very little redundancy.

- One advantage of the system is that 95% of the total water supply is supplied by gravity, largely mitigating the need for pumping stations supported by electrical power. (Reliance on gravity, however, would pose a huge threat if the area were subject to land subsidence.)

- There are 965 water sampling stations in New York City, in use since 1997. They consist of small cast-iron boxes with spigots inside them, raised 1.4 metres (4.5 feet) above the ground. Scientists from the city measure water from 50 stations every day. The samples are then tested for microorganisms, toxic chemicals and other contaminants that could potentially harm users of the water supply system. In 2015, the Department of Environmental Protection performed 383,000 tests on 31,700 water samples.

- The New York City water supply system leaks at a rate of up to 135 million litres (36 million U.S. gallons) per day. A complex five-year project with an estimated US$240 million construction cost was initiated in November 2008 to address some of this leakage.

- In 2018, New York City announced a US$1 billion investment to protect the integrity of its municipal water system and to maintain the purity of its unfiltered water supply.

Risk Assessment for the New York Water Supply System

Water supply risk is assessed in the context of the New York City water system in Table 2.

In the interests of brevity, we will not go through a detailed discussion of the rationale for each assessment made in Table 2. Instead we will highlight just a few assessments that are illustrative of the approach.

Earthquake Does Serious Damage to Water Supply System

The likelihood that the New York City supply system would be seriously damaged by an earthquake is considered to be speculative, as the area is not in a known fault area and has little or no history of significant ground movement. We would not make the same assessment in other parts of the world; for example, San Francisco in the United States.

Table 2: Risk Assessment for New York City Water Supply System

Principal Risk	Type	Risk Event	Likelihood of Occurrence	Geographic Scope of Impact	Extent of Impact	Controllability
Water goes elsewhere	Natural and human causes	Reservoirs are depleted due to hydrological changes caused by climate change, which causes rain and snow fall to decline in regions, and evaporation to rise, leading to drought conditions	Speculative. Rain and snow fall are unlikely to decline materially in this region of the country	Regional, but with international follow-on impacts	Existential	Preventable but unmitigable
	Human causes	Failure of a neighboring region's water system necessitates sharing of water supply; new aqueducts are constructed to share one region's water with another region	Very unlikely. Adjacent cities have good water supplies	Regional across multiple regions; international follow-on effects	Disruptive	Preventable and mitigatable
Water is there, but delivery system is disrupted	Natural causes	A significant earthquake or other major ground motion event causes aqueducts and pipes to break, causing shutdown of delivery system	Speculative. This is not an earthquake-prone area, nor is it subject to land subsidence	Regional across multiple regions; international follow-on effects	Existential	Unpreventable and unmitigable
	Human causes	Terrorists use nuclear bomb or massive conventional explosive to destroy reservoir dams and aqueducts, rendering the delivery system inoperable	Unlikely. The system is well-protected, but a successful attack can't be ruled out	Regional but with international follow-on impacts	Existential	Preventable and mitigatable
		Terrorists destroy underground water delivery pipes, leading to temporary shutdown of affected parts of system	Unlikely	Regional, but with international follow-on impacts	Endurable	Preventable but unmitigable

Principal Risk	Type	Risk Event	Likelihood of Occurrence	Geographic Scope of Impact	Extent of Impact	Controllability
		Maintenance of system is inadequate, neglected system deteriorates, leading to widespread or significant system failure	Unlikely. The system is relatively well-maintained and leakage is measured	Regional	Disruptive	Preventable and mitigatable
Water is there, but becomes undrinkable	Human causes	Terrorists poison the water, either in the reservoirs or in the aqueducts and pipelines, leading to emergency shutdown of system while water purification steps are undertaken	Unlikely. The system is well-protected, but a successful attack can't be ruled out	Regional, but with international follow-on impacts	Endurable	Preventable but unmitigable
		Industrial or agricultural pollution contaminates aquifer, making water undrinkable	Speculative. Development in the water supply region is managed	Regional, but with international follow-on impacts	Disruptive	Preventable by unmitigable

While the event is low in likelihood, if it were to occur the impact would likely be existential, as it would be impossible to move the eight million inhabitants of New York City elsewhere quickly. We anticipate that the damage to the aqueducts and tunnels would be sufficient that the water supply would be completely cut off to major parts of the city. Even with a significant mobilization effort, repairs are likely to take several months. It is unlikely that alternative water supplies, such as bottle or truck water, could meet the demand. To survive, people would have no choice but to vacate the city for several months until the water system was repaired, and water service was restored. Housing eight million people outside of the city for two months would be exceedingly difficult to organize, and many people would likely refuse to move. Significant loss of life is likely, particularly among the elderly and infirm, as they are not equipped to move and are likely to stay where they are and die.

Even if large portions of the population could be relocated temporarily, they would not be able to work. Without water, businesses in the city would need to close. Workers would have difficulty getting to businesses outside of the city, as the transportation system could not be reoriented to accommodate new commuting patterns. Governments would have little choice but to declare a two-month paid holiday for the entire area. The local economy would grind to a standstill.

And, since New York City is a world financial centre, the disruption could extend beyond the region, with global effects.

Starting the economy back up in the aftermath of the event would bring with it a large number of additional problems.

Finally, we consider this type of event to be unpreventable, primarily because it is unforeseeable.

We do not see many opportunities for mitigation if the event should happen. However, the completion of the first phase of Tunnel No. 3 brought a level of redundancy to the system. Prior to the completion of the first phase of Tunnel No. 3, the city was reliant on a single tunnel to bring water to Manhattan.

Climate Change Causes Source Water to Deplete

The likelihood that the New York City water supply would be depleted due to drought brought on by climate change is also considered to be speculative, as the area is in a temperate zone and it is as likely that rainfall will increase as it is that it will decrease. We would not make the same assessment in more arid areas of the world, including the southwestern United States and parts of Africa and the Middle East. However, if water depletion were to occur in any region, the impact could be existential. The gradual emergence of the supply shortage would be a mitigating factor, unlike the earthquake scenario. However, forced migrations represent an unprecedented disruption in the fabric of society; civil disorder and potentially chaos should not be unexpected.

Disruption to the Supply Network

Human disruption of the New York City supply network seems relatively more likely, given that the city remains a target for potential attacks; we have classified it as unlikely. Of course, New York is a wealthy city, of strategic importance to U.S. national interests, so we assume that substantial prevention activity is ongoing. The impact of such an event would be existential, due to the inability to replace the water supply for such a large population.

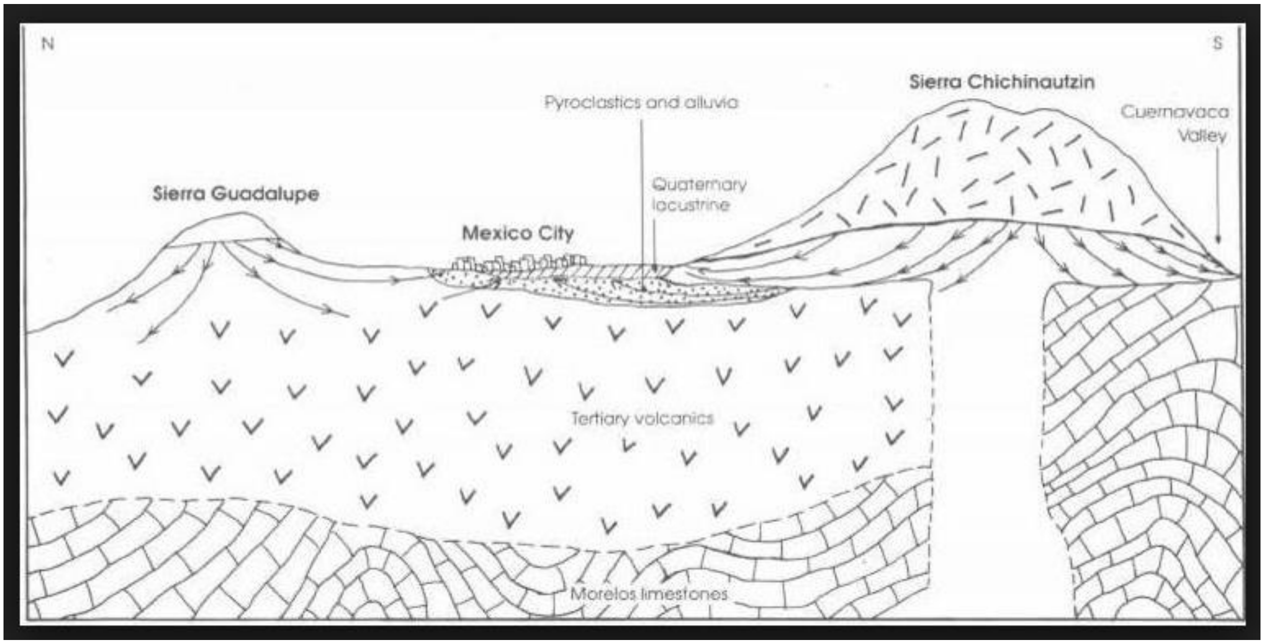
Case 2: Mexico City Water System

Overview of the Mexico City Water System

Mexico City was founded on the concept of water. When the ancient city of Teotihuacán was founded in 1325 AD by the Mexicas, its chosen location and further development were influenced by a longstanding water prophecy. The Mexicas believed that their god would show them where to build a great city by providing a sign – an eagle eating a snake while perched atop a cactus. When the Mexicas saw the vision come true on an island in the middle of beautiful Lake Texcoco, they decided to build a city there in the midst of the vast supplies of fresh water. At the time it seemed like both a perfect religious and societal choice, as the lake would fill up like a basin whenever rain would fall. A large system of dikes and levees were eventually constructed to offer control and relief from the rain. The Mexicas, who would later be known as the Aztecs, would never come to realize the final irony of their choice. Their city in the middle of the lake would evolve to become the site of a growing modern water supply crisis.

The issues with Mexico City's water supply stemmed from decisions taken by Spanish Conquistadors, who arrived in the 16th century and eventually conquered the Aztecs. In an effort to spur expansion and development, the Spanish began over the next hundred years to drain the lakes around the city. With Mexico City trapped at the bottom of a closed valley, and no natural rivers flowing in or out, the city ultimately came to rely on new rainfall and access to an underlying aquifer for its prime water sources. Eventually, modern Mexico would be forced to contend with its capital city's water scarcity issue that was hundreds of years in the making.

Chart 3: Mexico City Topography and Aquifer Pressures



Source: Mexico City – Aquifer Pressures by Tom Phillips

Mexico City is now by far Mexico's largest city and the most populous metropolitan area in the Western Hemisphere. The city has grown to 20 million residents and enjoys up to 40 million visitors every year. It sits 2,100 metres (7,000 feet) above sea level and stretches over nearly 2,500 square kilometres (1,000 square miles). With the World Health Organization indicating a single person requires between 50 and 100 litres of water a day (13–26 U.S. gallons) to meet basic needs, the demands on the daily water supply of a city of this size can be straining on the local infrastructure and natural water supplies. The Mexico City valley receives about 700 millimetres (28 inches) of annual rainfall, which is concentrated from June through to September with little or no precipitation during the remainder of the year.

At first, the modern advances to solve the water supply, along with irrigation and sewage issues, within the city were fruitful and commendable. The Grand Canal, a marvel of early-20th-century hydraulic engineering, was completed in the late 1800s and provided helpful relief by protecting the city from flooding and collecting rainwater. The design was incredibly thoughtful as the Grand Canal collected rain and sewage from the city centre and took it first to the east towards Lake Texcoco, and then through the mountains of the north. In the north of the city, it could be used to irrigate the growing, sprawling agricultural fields of the Valle de Mezquital. The federal government, placed in charge of regulating the use of water resources, organized the financing of investments and supplying of water resources (including additional bulk water from other river basins) through the National Water Commission, called Conagua, in 1992.

The ultimate limitation of the Grand Canal, and other water projects developed by Conagua, is their reliance on gravity. Appropriately, with gravity as the one true constant, systems historically were constructed with the premise that water would naturally run downhill. The issue became, however, that what was "downhill" in Mexico City became increasingly difficult to predict. With the metropolis set on a destabilized lakebed, in the middle of a valley surrounded by mountains, Mexico City began to experience significant land subsidence. The sinking of the city meant that the Grand Canal lost its slope in the decades after its completion. Today, engineers battle gravity to pump the vast amounts of sewage waste water (agua negra) uphill through the canals.

Fresh water supplies today in Mexico City are now fortified by external sources far distant from the city centre. Hundreds of miles of pipes bring in water from distant lakes and rivers, providing approximately 30% of all water consumption. In the valley and underlying aquifer, approximately two times as much water is pumped out of the aquifer than is refreshed by rainfall. Eastern stretches of the city often have no water coming from the plumbing during dry seasons. In many areas, local water pressure is often insufficient or unreliable.

The internal city system also suffers from deteriorating infrastructure and is impacted by the shifting sands beneath the city. Half of the system is over 60 years old. It is estimated that up to 40% of the water that flows through the system may be wasted through leaks in the infrastructure, according to a recent public study. The maintenance is additionally exacerbated by the sinking of the city, which puts extreme pressure on pipes and supplies. Estimates note that the underlying water table is dropping as much as 15 inches per year in some areas. Recent water control systems have helped move water out of the city quickly as needed to avoid sewage issues, but also reduces how much water is returned to replenish the aquifer.

Water tanker trucks provided by the government are now employed to provide relief, but water quality is poor and often is only used by consumers for flushing toilets or washing floors and sidewalks. The secondary market for water has grown exponentially, with some consumers buying private water from pre-arranged truck services with very high demand. In many places, the economics are such that families can spend as much as 20% of their income on usable water. Some inhabitants of the city are beginning to look at rain collection and purification systems that can assist in reducing their overall cost of water access and consumption.

As an aside we would note that high water costs are not unique to Mexico City, and do not always manifest themselves as currency costs. For example, in parts of Africa the water supply system is sufficiently underdeveloped that people are required to walk long distances every day to draw fresh water from the nearest well (because there is no way to store it and there are obvious limits on how much they can carry). In these cases, they devote a significant portion of their labour, rather than cash, to obtain basic water needs. In both instances people's quality of life is reduced by requiring that they bear excessive water costs; the costs are an impediment to economic growth.

The risk of depletion of the water supply may grow in coming years. With increasing economic development in the city, the potential for urban sprawl continues. In addition, hotter weather due to a changing climate has the potential to affect future rainfall and encourage more rapid water evaporation within the city. The threat to the water supply in Mexico City is existential and probable.

Risk Prevention and Mitigation Activities Relating to the Mexico City Water Supply System

As noted, current risk prevention in the Mexico City system centres around identifying and bringing external water sources to the city, as well as maintaining the pumping infrastructure to capture flow in the Grand Canal. Major flood inundation and major water supply interruption are significant concerns. In 2009 the federal government launched a formal water sustainability program for the Mexico City valley, with focus over time on substantial risk prevention and mitigation activities to protect the public from water supply risks. Specific objectives identified are to prevent floods from inundating the current systems, treat all wastewater collected within the system and reduce overexploitation of groundwater.

Table 3: Risk Assessment for Mexico City Water Supply System

Principal Risk	Type	Risk Events	Likelihood of Occurrence	Geographic Scope of Impact	Extent of Impact	Controllability
Water goes elsewhere	Natural and human causes	Reservoirs are depleted due to hydrological changes caused by climate change, which causes rain and snow fall to decline in region, and evaporation to rise, leading to drought conditions	Unlikely. Climate change likely to affect region, with longer, hotter dry seasons. Impact on aquifer is uncertain	Regional	Existential	Unpreventable and unmitigable
	Human causes	Population growth and continuing development of tourism strongly increase demand for water	Likely and happening today	Regional	Disruptive	Preventable and mitigatable
Water is there, but delivery system is disrupted	Natural causes	A significant earthquake or ongoing land subsidence causes aqueducts and pipes to break and gravity to overwhelm pumping stations, causing failure of delivery system	Speculative	Regional	Existential	Unpreventable and unmitigable
	Human causes	Terrorist activity damages or destroys secondary water source of dams and aqueducts, rendering the delivery system inoperable	Unlikely	Regional, but with international follow-on impacts	Disruptive. Population may need to be relocated	Preventable and mitigatable
		Maintenance of system is inadequate, neglected system deteriorates, leading to widespread or significant system failure	Unlikely	Regional	Disruptive	Preventable and mitigatable
Water is there, but becomes undrinkable	Human causes	Severe flood fills lake bed areas and inundates water maintenance system operations	Speculative	Regional	Endurable	Preventable and mitigatable
		Intermixing of water and sewage occurs, making water undrinkable	Speculative	Regional	Disruptive	Preventable and mitigatable

Risk Assessment for the Mexico City Water Supply System

Table 3 presents our assessment of the risks to the Mexico City water supply system. As can be seen, the system is at substantially greater risk than the New York City system.

Mexico City has already suffered from the damaging effects of ground movement, in the form of land subsidence. This has been mitigated by the introduction of pumping stations to move water (and sewage) uphill. However, the pumping stations increase the risk because they increase the system's reliance on electricity. Subsidence is likely to continue, necessitating ongoing mitigation efforts in this area.

Mexico City is very much at risk from climate change, which may lower rainfall levels in the region. This will place greater pressure on the aquifer, which is already being depleted. Ultimately the region would become uninhabitable if the water supply is depleted. Alternatives such as desalinization plants would probably take too long to construct, and a large-scale migration of the population could become inevitable.

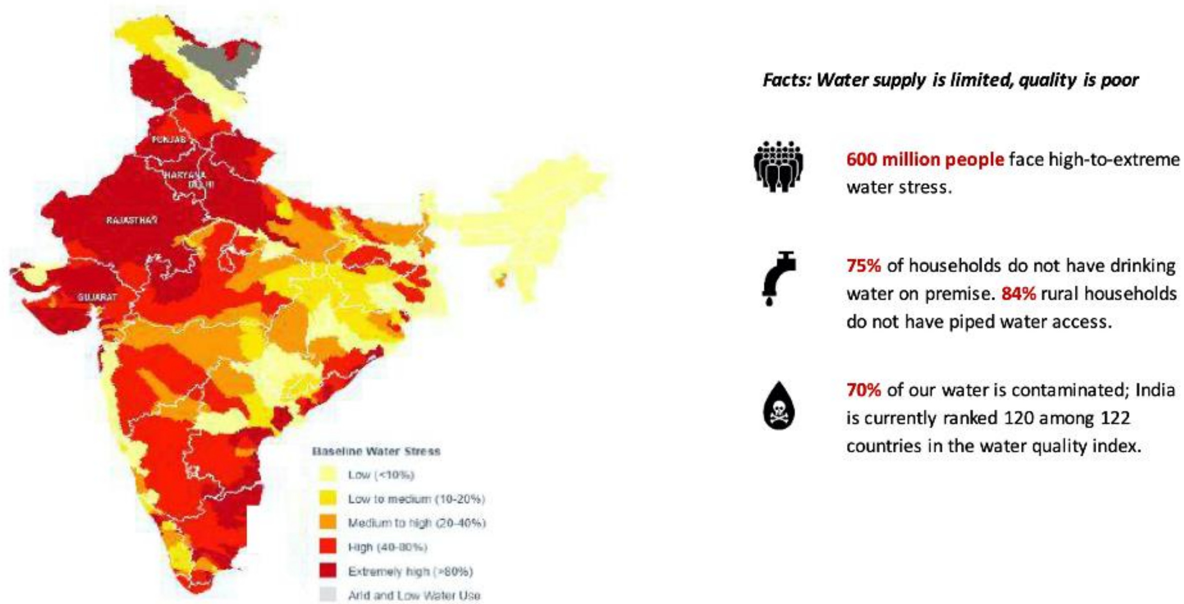
In addition to long-term solutions, prevention efforts will need to focus on repairs to the existing infrastructure, to reduce the water loss from pipe leakage.

Case 3: The Indian Water Supply System

Overview of the Indian Water Supply System

India will soon become the most populous country in the world, with more than 1.3 billion people. While the Indian subcontinent receives significant rainfall across much of the country, and snow over its northern mountain ranges, water supplies are subject to a range of issues, including seasonality of precipitation, inadequate infrastructure, poor sanitation in many places and depletion of groundwater supplies. India's dependence on snowmelt runoff from northern mountains exposes it to future challenges from a warming climate.

Chart 4: Geography of Water Stress in India



(Ratio of total water withdrawals to total flow, in 2010)
Source: NITI Aayog – Composite Water Management Index; https://niti.gov

Until recently, most major cities in India lacked adequate clean water supplies and sanitation. In many rural areas the situation is serious, with the government launching major programs to increase access to toilets and reduce past issues with open defecation. The World Bank has estimated that 21% of communicable diseases in India are linked to unsafe water.

Serious additional problems are on the horizon. In many regions groundwater supplies are being depleted rapidly and it is estimated that groundwater accounts for up to 40% of the country's supply. Recently Bangalore, a major city in southern India, experienced extreme water shortages driven by limited groundwater and a late start to the annual monsoon season.

From a risk management perspective, India has several sources of risk, some of which are not commonly found in Europe or North America. Physical risk due to flooding and drought is important and likely to be compounded by climate change, similar to issues faced worldwide. However, India also faces major challenges due to high population growth, economic development, urbanization, a rapidly growing middle class and underdeveloped sanitation.

Risk Prevention and Mitigation Activities Relating to the India's Water Supply System

The country has made major strides in improving its citizens' access to drinkable water and sanitation. In 2005, none of the cities in India with a population of more than one million provided water for more than a few hours per day. Significant progress has been made since then, with almost 90% of the urban population having access to water and "basic sanitation". The Indian government has taken aggressive steps to improve the situation, including supporting the creation of a water management index tool by NITI discussed in the above-referenced 2018 report.

Actions being taken in India include:

- A major commitment by the Indian government to recognizing and measuring the problem, including the creation of the water management index;
- Building infrastructure, including water systems and 90 million toilets;
- Forcing consumers to pay tariffs (bills) for water use to encourage efficient use (significant numbers of households in India do not pay their water bills, creating an absence of incentives to not waste water);
- Improving catchments and retention of water from wet to dry seasons; and
- Controlling excessive use of antibiotics in agriculture or health care.

The final point above illustrates an important aspect of how water management issues in one part of the world can affect others, posing a different type of risk management problem than New York and Mexico City. In addition to challenges with access to potable water, serious sanitation issues, combined with India's well-documented[1] extensive use of antibiotics (often to combat the effects of poor-quality drinking water), are contributing to a major global risk exposure involving "superbugs", or antibiotic-resistant bacteria. While India is certainly not the only country driving this global problem, it is a contributor and serves as an illustration of how water problems can manifest themselves in indirect ways, not just direct ways like floods, droughts or agricultural failures. It also illustrates how risk management actions such as the reduction of water-borne diseases through the use of antibiotics can increase other risks, even outside the region where the water issues arise.

Risk Assessment for the Indian Water Supply System

Table 4 presents our assessment of the risks to the Indian water supply system. It shows that India's risks are far from unlikely or speculative, in contrast to New York City. India's risks are current and severe. As in the other examples, in the following table we present only an illustrative risk assessment for the country. A proper assessment of the actual situation would require an extensive discussion beyond the scope of this paper.

1 For example, see www.newslaundry.com/2017/10/09/antibiotic-resistance-india-superbug-ndm-1. The story includes many links to various studies and documentation of the issue.

Table 4 : Risk Assessment for Indian Water Supply System

Principal Risk	Type	Risk Events	Likelihood of Occurrence	Geographic Scope of Impact	Extent of Impact	Controllability
Water supply and amount	Natural and human causes	Water supplies become more erratic due to hydrological changes caused by climate change, which causes delays in the onset of the monsoon, declining snowfall in northern mountains, increased intensity of rainfall, and more intense tropical cyclones	Imminent. Extreme precipitation, floods	National	Highly disruptive	Unpreventable and mitigatable
	Human causes	Population growth, development, and growing middle class increase demand for water	Certain and happening now	National	Highly disruptive	Unpreventable and mitigatable
		Growth of middle-class changes demand for types of food, shifting to more meat, poultry, and dairy. This may create stresses on water supplies in locations which produce these foodstuffs	Likely	National	Somewhat disruptive	Preventable and mitigatable
Water is there, but delivery system us disrupted	Natural causes	Increased flood risk from climate change (e.g. extreme cyclones, melting snowpack, and higher rainfall intensity) damages water supply delivery systems such as reservoirs, dams, and pumping stations	Speculative	Regional across multiple regions; international follow-on effects	Existential	Preventable and mitigatable
	Human causes	Excessive reliance on groundwater depletes aquifers	Likely within five years	Major cities nationwide	Highly disruptive	Unpreventable and mitigatable
		Poor systems for measuring water use lead to many people not paying tariffs, thus removing an economic incentive to conserve water	Exists now	Regional	Endurable but inefficient	Preventable and mitigatable

Principal Risk	Type	Risk Events	Likelihood of Occurrence	Geographic Scope of Impact	Extent of Impact	Controllability
		Building of dams, for example on upper Ganges, damages water supplies downstream near Kolkata or in Bangladesh	Likely	Regional and international	Disruptive	Preventable and mitigatable
Water is there, but becomes undrinkable	Human causes	Poor sanitation leads to contamination of water supplies, increasing disease risk	Certain and happening now	National	Highly disruptive	Preventable and mitigatable
		Increased disease from unclean water leads to excessive use of antibiotics for humans and agriculture, contributing to risk of “superbugs” and/or global pandemic	Speculative	International	Catastrophic	Preventable and mitigatable

5. Broader Perspectives

The three cases presented above were chosen to give the reader a sense of the spectrum of water supply risk levels. By no means are they intended to be comprehensive. The risks in each region will be unique; the risks could be more or less significant than depicted here. Space and time prevent us from considering other cases in, for example, Africa, Asia or the Middle East.

One can, however, extrapolate from these three cases to consider the risk from a global perspective. It is clear from our analysis that we are facing a looming water crisis, of existential proportions, in some parts of the world. Water supplies in some regions will simply run out, as they may in Mexico City. In other regions the supply may remain, but the water will become non-potable. In still other regions, like New York City, water supply is not a significant issue unless there is a successful attack on the system. Absent an attack, the disparity between high-functioning and poorly functioning systems is likely to increase.

Water supply issues are not simply a “wealthy versus poor” country issue. While the situation in New York City looks quite bright, there are other parts of the United States where the situation is not as positive. For example, there are numerous newspaper reports of looming massive infrastructure failure in California, due to inadequate maintenance of the water delivery system there. Similarly, the aquifer in the central plains states in the United States is declining at a rate that some find alarming. This latter issue has implications beyond basic water needs, as the aquifer is fundamental to U.S. food and gasohol production.

To the extent that significant water supply risk events emerge gradually, the most likely response will be migration away from the affected area to an area where the issue has not emerged. For example, it is not unreasonable to consider the possibility that at some point a significant portion of the population of Mexico City will need to relocate, putting pressure on other regions of Mexico and other countries, such as the United States. From a humanitarian standpoint it will be hard not to allow this migration to occur, given that the alternative may be deaths on a large scale. Migration will start with those who have the means to do so; however, when the water supply issue reaches the critical stage, even those without means will attempt to migrate.

If the emergence of significant water shortages is more rapid, chaos and large numbers of deaths may be the result.

Even in areas where the water supply situation is relatively stable, an attack on the water supply could be extremely disruptive to a region.

In addition to the direct risks to the water supply, mitigation activities in some regions may have very negative follow-on effects. The routine use of antibiotics to combat diseases related to water contamination may eventually lead to superbugs that could spread globally. Thus, even in countries with low water supply risk, there are still significant risks from water supply issues. In the United States alone, it is estimated that two million people each year are infected with bacteria that is resistant to antibiotics, and at least 23,000 people die as a result. The elapsed time from when a new antibiotic is developed and introduced to the time where antibiotic resistance is first identified is growing ever shorter. While the resistance is clearly not immediately universal across all individuals in the population, there is a growing trend of encountering mortality and health issues due to antibiotic resistance. The highest concerns are the high rates of antibiotic resistance in markets where there in strong dependence on a small number of antibiotics, and/or the opportunity to quickly bring large quantities of new antibiotics into the health delivery systems is a challenge.

Actuarial models of the impacts of antibiotic resistance, even in high-income population markets, indicate that the issue is of growing importance, and that crude resistance rates can be especially high at older ages. These models imply higher health care cost trends of insured populations, and place additional strain on social healthcare systems.

The actuarial research report “National Risk Management: A Practical ERM Approach for Federal Governments” by Sim Segal, FSA, CERA, sponsored by the Casualty Actuarial Society, Canadian Institute of Actuaries and Society of Actuaries, notes several places where an actuary serving as a National Risk Officer needs to consider the importance of the water supply. Many of the national risks identified in the paper related to water on a national level are also very applicable to large municipalities or regions that rely on a common water source.

Risk management objectives for large cities include managing life and health risks to protect the lives of citizens, and to protect and enhance the public health of citizens; and the creation, protection and maintenance of a quality water supply are among the key operations for the city. The report notes that risk metrics such as increasing the local population’s healthy life expectancy and increasing the perception of adequate health safety can be tracked and monitored, and active risk management can be done by setting standards for clean air and water.

Key operational risks that should be monitored include:

- Maintenance of water quality;

- Protection against illegal disposal of toxic waste that could contaminate the water supply; and
- Protection against industrial accidents or pollution that would lead to contamination of the water supply.

6. Implications for Financial Security Systems

Water resource risks have implications for life, health, agriculture and property insurers. In addition to private insurers, there are government-sponsored social insurance systems within each of the above categories. Implications fall on both the liability and asset sides of the balance sheet. Many insurers are already responding to these challenges. Actuaries need to consider whether and how prices should be adjusted in light of water resource risk, whether coverage terms should be altered and whether reinsurance protections should be revisited.

Insurers of all types will need to assess their real estate investment portfolio in light of water resource risk, as properties in affected areas could lose substantial value. In addition, to the extent that local business activity is disrupted by a water supply issue, equity market values could decline and defaults on credit instruments could rise; in both cases the financial dislocations could be precipitous.

Agriculture insurers will need to monitor trends in water resource management and recognize that historical data on variations in crop yields may lose relevance. A severe water shortage could create catastrophic claims for crop insurers.

For life insurers, water resource risks pose a concentration risk problem, as death rates could spike in an area where the water supply is disrupted. In addition, to the extent that water availability and quality continues to deteriorate in some areas, future mortality is likely to be different than in the past.

Overall public health is strongly correlated with water quality. Reducing the risks of poor water quality, limited access to water resources and consistency of clean water will have a direct, favourable impact on future health care costs. The converse is equally true: lack of attention to water resource risk management may lead to spiralling health care costs. And of course, in a catastrophic collapse of a water supply system, local health systems and health insurers could be overrun with sick patients, with costs that neither private nor public health care plans can afford.

For property insurers, the most direct impact of a water supply collapse would be the potential for business interruption claims. While these may not be covered under existing policy terms, there may be intense political pressure to pay the claims anyway. A secondary effect is the potential for property in large areas to lose resale value, as residents move away from affected areas. Because replacement costs are likely to remain unchanged, this type of situation could create a large-scale moral hazard for insurers, as insureds with mortgages greater than market values may be tempted to burn down or otherwise destroy their properties. In addition, there is the potential for civil unrest in affected areas and looting of deserted areas, with the attendant damage to property.

For social security and pension plans, the implications could be significant to the extent that economic activity is seriously disrupted, affecting the funding of the programs.

7. Next Steps

While our paper has focused primarily on the actuarial approach to water resource risk management, the actuarial profession can contribute more broadly in the analysis of the economic and financial consequences of water resource disruptions. The work would, of course, need to be collaborative with other experts. Actuaries increasingly collaborate with business, government and other professionals to improve all parties' understanding of issues. For example, we can assist in the construction of models showing how specific events might evolve for a particular water system. This might lead to potential mitigation or adaptation strategies, and help in the prioritization of expenditures.

Assessing water resource risks will become more important as the impact of climate change increases. A global system of ongoing assessments, around a common risk framework, would be useful, particularly as the need for climate change mitigation accelerates. We encourage other actuaries to become involved in the water resource risk issue.

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