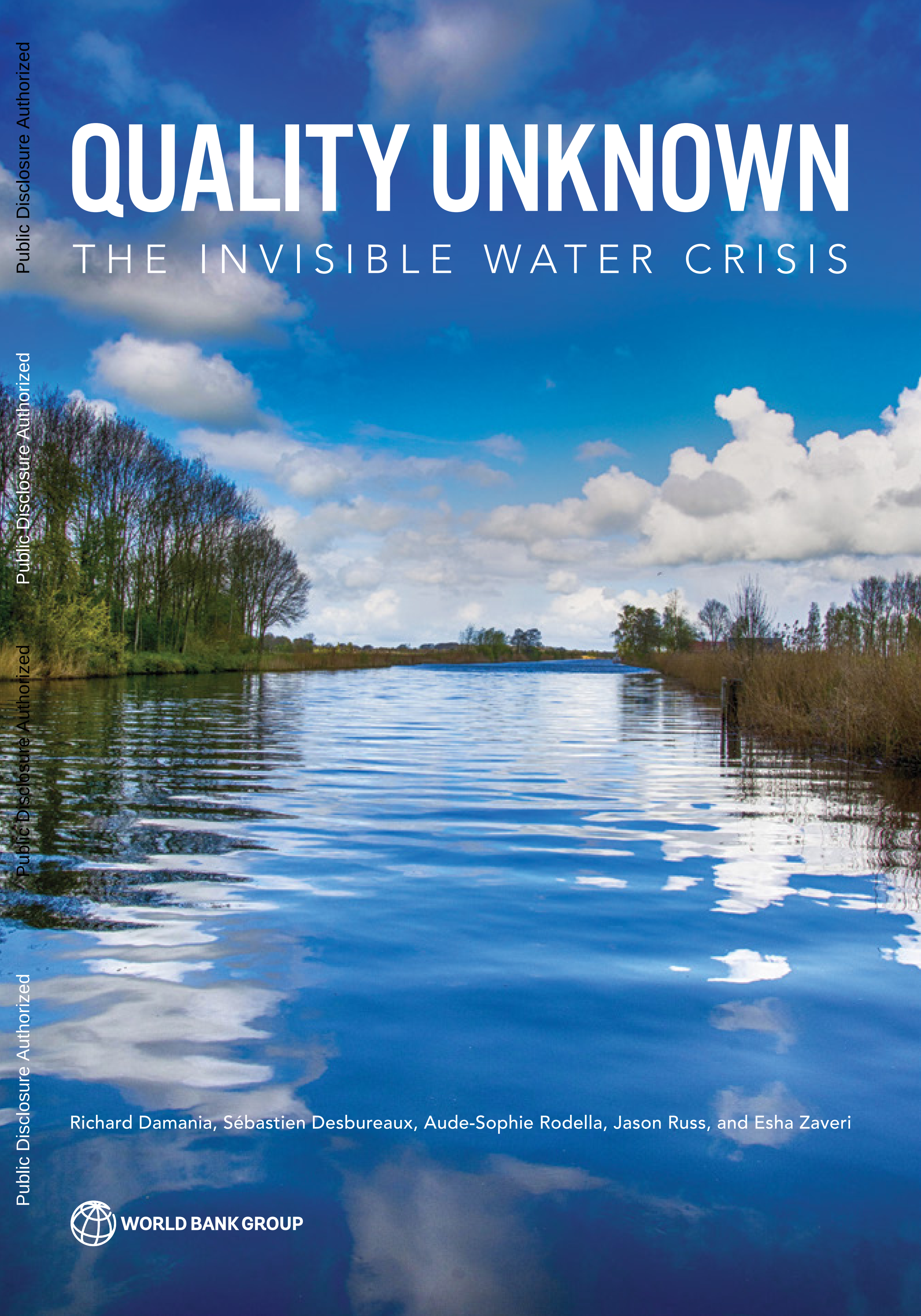

QUALITY UNKNOWN

THE INVISIBLE WATER CRISIS

Richard Damania, Sébastien Desbureaux, Aude-Sophie Rodella, Jason Russ, and Esha Zaveri

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EXECUTIVE SUMMARY

It was the summer of 1969 and the Cuyahoga River was on fire. This wasn't the first time the river in northern Ohio had burned—it wasn't even the tenth. Every few years, an errant spark would ignite the river, threatening nearby buildings or passing ships. The fire of 1969 was not especially notable for the damage it caused or the duration of its blaze. But it did ignite the tinderbox of environmental unrest that had already been smoldering across the country. Within six months of the fire, the U.S. Congress passed the National Environmental Policy Act, establishing the U.S. Environmental Protection Agency (EPA). One of the first acts of the EPA was to implement the Clean Water Act of 1972, which mandated that all waterways must be of sufficient quality to be safe for swimming and aquatic life by 1983.

Fifty years on, water quality issues remain a challenge. Like the Cuyahoga River in 1969, many other water bodies are on fire—some literally, like the Meiyu River in eastern China or Bellandur Lake in Bangalore, India, which has rained ash onto buildings up to six miles away. Yet most burn imperceptibly, with bacteria, sewage, chemicals, and plastics sucking out the dissolved oxygen much like a raging inferno and transforming water into poison for humans and ecosystems alike. Understanding of this problem has been impaired not just by a lack of information, but also by the complexity of issues that often transcend discipline boundaries—environmental science, health, hydrology, and economics—with each offering different insights.

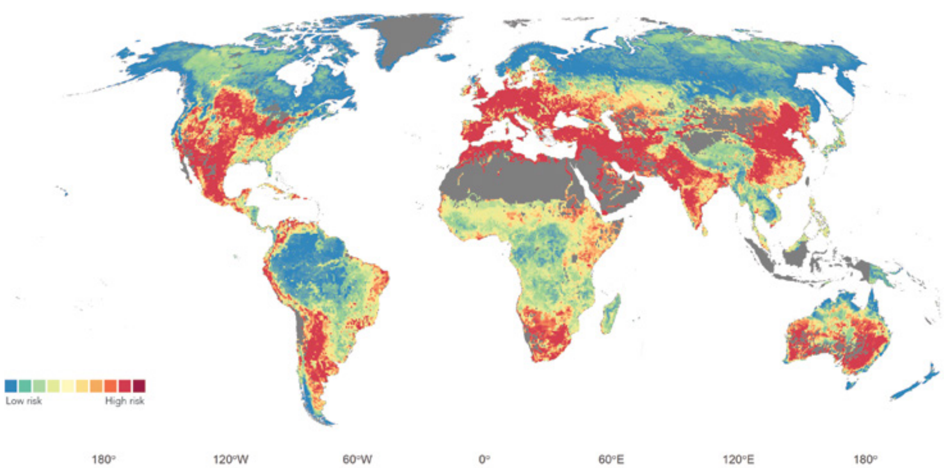
This report brings forth new results that illuminate the impacts of the hidden dangers that lie beneath the water's surface and elucidate strategies for combating them. The main, though not exclusive, focus is on the parameters that are tracked in the water quality Sustainable Development Goal (SDG) 6.3.2, with its focus on nutrient loads, salt balances, and overall environmental health of water bodies. The report demonstrates that the parameters identified in SDG 6.3.2 have impacts that are wider, deeper, and larger than previously known, suggesting the need for a broader focus on water quality beyond indicators of sanitation-related contaminants such as fecal coliforms and *Escherichia coli*. Recognizing the scope of the problem, identifying the magnitude of the impacts, and formulating ways to address these will be critical to improving public health, preserving ecosystems, and sustaining economic growth throughout the twenty-first century.

UNDERSTANDING THE EXTENT OF THE PROBLEM

The complexity of water quality and the multitude of parameters that need tracking are at least partly why global water quality monitoring has proved so troublesome. To shed light on the issue, this study assembled a vast, and perhaps the largest, database on water quality. Data were collected from beneath the surface using information from in situ monitoring stations or samples. Satellites collected data from the sky using remote-sensing techniques. Other data were generated by computer using machine learning models. The latter are particularly interesting because monitoring stations and remote sensing provide data for limited points in space and time, while modeled data can fill gaps to provide a more complete picture of the state of water quality. Harnessing all of this evidence provides some stark insights.

Rich and poor countries alike endure high levels of water pollution. Map ES.1 displays the overall global water quality risk for the three major water quality indicators of SDG 6.3.2: nitrogen (nitrate-nitrite), an outlier pollutant in terms of scale, scope, trends, and impacts; electrical conductivity, a measure of salinity in water; and biological oxygen demand (BOD), a widely used umbrella proxy for water quality. It is clear from map ES.1 that high-income status does not confer immunity from water quality problems. This contradicts what one might assume based on the environmental Kuznets curve hypothesis, which posits that pollution eventually declines with prosperity. Not only does pollution not decline with economic growth, but the range of pollutants tends to expand with prosperity. The United States alone receives notices for the release of more than 1,000 new chemicals into the environment each year—or around three new chemicals per day. Keeping up with such a growing range of risks is difficult even in countries with significant resources and nearly impossible in developing countries.

MAP ES.1: Water Quality Risk for Biological Oxygen Demand, Nitrogen, and Electrical Conductivity



Note: This map shows a water quality index summarizing global predictions for biological oxygen demand, electrical conductivity, and nitrogen. Each value is scaled to a common support for comparability and then summed together. Average values for 2000–10 are displayed. Gray areas have no data for one or more parameters. More details on the construction of the index are presented in the appendix (available at www.worldbank.org/qualityunknown).

WHY IT MATTERS

Results in this report demonstrate the importance of water quality across a range of sectors and how its impacts cut across nearly all SDGs. Water quantity challenges receive a great deal of attention from the development community, but water quality impacts may be equally, or more, important. This report describes results of new analyses that find larger impacts on health, agriculture, and the environment than were previously known. When these sectoral impacts are aggregated, they account for significant slowdowns in economic growth. Well-known pollutants such as fecal contaminants, as well as new pollutants, including nutrients, plastics, and pharmaceuticals, present significant challenges.

Nitrogen is essential for agricultural production but is also volatile and unstable. Frequently more than half of nitrogen fertilizer leaches into water or the air. In water, it may result in hypoxia and dead zones—problems that arise from a lack of dissolved oxygen in water that can take centuries to recover. In the air, it may form nitrous oxide, a greenhouse gas that is 300 times more potent at trapping heat than carbon dioxide. This is why some scientists suggest that the world may have already surpassed the safe planetary boundaries for nitrogen and that it is the world's greatest externality, exceeding even carbon.

Although it is known that oxidized nitrogen can be lethal to infants, this report shows that those who survive its early consequences can be scarred for life—impairing growth and later-life earnings. Nitrogen in water is responsible for fatally inflicting what is known as blue baby syndrome, which starves infants' bodies of oxygen. This report finds that those that survive endure longer-term damage throughout their lives. Infants born in India, Vietnam, and 33 countries in Africa who were exposed to elevated nitrate levels in the first three years of life grew up shorter than they would have otherwise. This result is striking for three reasons: First, it means that nitrate exposure in infancy can wipe out much of the gain in height (a well-known indicator for overall health and productivity) seen over the last half century; second, it suggests that nitrates may have similar or worse impacts on height and other development metrics as fecal coliforms; and finally, impacts are found in even geographies where nitrate levels are below levels presumed safe.

These new findings suggest a stark trade-off between using nitrogen as a fertilizer, where it confers benefits to agriculture, and economizing on its use to protect health. A simple calculation quantifies this trade-off: Globally, an additional kilogram of fertilizer per hectare increases yields by 4–5 percent. However, the subsequent fertilizer runoff and release of nitrates into the water poses a risk large enough to increase childhood stunting by 11–19 percent and decrease later-life earnings by 1–2 percent. A conservative interpretation of this finding suggests that the vast subsidies accruing to fertilizers likely generate damage to human health that is as great as, or even greater than, the benefits that they bring to agriculture.

Salt, the most elementary contaminant that has plagued the world since antiquity, is on the rise in soils and bodies of water throughout the world. This report presents new research that documents the extent of the impact of salt on agricultural production. Sumer, the civilization that gave us the wheel, plough, and written language, was also the first to pioneer irrigated agriculture. In doing so, it led to an accumulation of salts that destroyed agricultural potential and led to the eventual decline of the great civilization. Today, saline waters and soils are spreading throughout much of the world—especially low-lying coastal areas, irrigated drylands, and around urban areas—with large impacts on agricultural yields. This report quantifies the effects on yields and finds they fall almost linearly with salt concentrations in water. Overall, enough food is lost each year because of saline water to feed 170 million people, or a country the size of Bangladesh.

Saline drinking water is harmful for human health, particularly in the vulnerable phases of the life cycle—infancy and pregnancy—compromising human development. In Bangladesh, where saline water is widespread, it is responsible for up to 20 percent of infant mortality across the most affected coastal areas. Pregnant women exposed to high amounts of salt are more likely to miscarry and are at a greater risk of preeclampsia and gestational hypertension. But new research finds visible effects even in areas with lower levels of salinity than in Bangladesh, where fetal deaths are found to rise by as much as 4 percent in saline regions. When babies exposed to high salinity levels survive, they are at higher risk of health complications. Despite this, there are no health-based drinking water standards for salt.

Pollutants of emerging concern such as microplastics and pharmaceuticals exemplify the complex nature of water quality issues: multifaceted, with no immediate or obvious solutions. The usefulness of plastics and pharmaceuticals is immeasurable, and yet the unintended by-products have consequences that are widespread and difficult to quantify and contain. Microplastics, the broken-down product of consumer goods, plastic bags, and other polymeric materials, are ubiquitous throughout the world. Although there is uncertainty about the extent of the problem, some studies have detected them in 80 percent of global freshwater sources, 81 percent of municipal tap water, and even 93 percent of bottled water. Although there is growing concern that ingesting microplastics and nanoplastics can be harmful to human health, there is still limited information about where safe thresholds might lie. Removal of plastics, once in water, is difficult and costly. Voluntary approaches to reduce, reuse, and recycle plastic, though popular, can only go so far and will not resolve the problem without the right mix of regulations and incentives. Prevention is therefore key, as is a better understanding of these hazards and the need for standardized methods for exposure and hazard assessments.

Given the range of contaminants, is it possible to determine the total economic cost that bad water quality has on economic activity? The multitude of contaminants, the complexities of measurement, and the uncertainty of impacts leave that question unanswered. However, it is possible to provide an indication of the relationship between upstream water quality and downstream economic activity using several recently available, spatially disaggregated data sets on economic activity, measured by gross domestic product (GDP), water quality, and other parameters of relevance.

The release of pollution upstream acts as a headwind that lowers economic growth in downstream areas, reducing GDP growth in downstream regions by up to a third. Although many water quality parameters may affect growth, BOD is perhaps the most appropriate measure to use to test the relationship between upstream water quality and downstream GDP, given its ability to proxy a wide array of pollutants. When the BOD level of surface water is at a level at which rivers are considered heavily polluted (exceeding 8 milligrams per liter), GDP growth in downstream regions is lowered by a third. This is yet another stark indication that there are often trade-offs between benefits of economic production and environmental quality, and that the externalities generated by economic production can be circular, reducing growth downstream.

POLICIES TO TAME THE WICKED PROBLEM

Water quality is a problem that is growing in complexity as prosperity expands and new contaminants emerge. The increasing range of pollutants varies by sector, geography, and development level. There are still deep uncertainties about safe levels and the size and type of impacts on humans and ecosystems. Not only is there no silver bullet solution to solve the water quality problem, but even coming up with a typology of appropriate responses is challenging. Measuring, understanding, and regulating water quality combines the ingredients of a "wicked problem," a term coined by design theorists Horst Rittel and Melvin Webber to describe complex matters for which there are no optimal solutions.

Faced with these wicked challenges, there are three approaches available to policy makers: a passive approach of inaction, a proactive approach of prevention, or a reactive approach that treats contaminants (figure ES.1). Policy inaction is common in low-income countries or where there is uncertainty about the effects of pollutants. Responses to perceived hazards are then left to individuals, who may, for instance, relocate to a safer area or

FIGURE ES.1: Three Main Approaches to the Wicked Problem

1. PASSIVE
Policy inaction

2. PROACTIVE
Prevent, abate, or mitigate

3. REACTIVE
Treat or purify

circumvent the effects through private avoidance actions. Where regulatory capacities are higher, policy makers can be proactive and seek to prevent or reduce pollution at the source. Alternatively, they may be reactive and attempt to treat the toxic discharges, typically through investments in various types of water treatment facilities.

The way forward requires a mix of these approaches, tailored to reflect the specificities of the water quality challenges at hand. First, it requires obtaining more information about the scale and scope of the problem and making it available to affected parties in an open and transparent manner. Next, it requires better incentives to prevent pollution from entering the environment. As the adage goes, an ounce of prevention is often better than a pound of cure, and given the high uncertainty in regard to impacts, prevention is often the safest alternative. Finally, because it is cost prohibitive to prevent all pollution, smart investments must be made to effectively treat pollution. Each of these pathways is described in figure ES.2, which summarizes a ladder of interventions that begin at relatively lower effectiveness but are more easily implementable and then increase in complexity and impact.

Improving the measurement of water quality is a critical first step. Few developing countries adequately monitor water quality. New technologies and techniques have made measurement more feasible and reliable. Recent trials have demonstrated that multilayered monitoring systems involving several parties can improve the reliability of data collected. These in turn can be complemented with remote sensing and machine learning to provide an additional and independent layer of verification. Blockchain technologies, though still in the experimental stages of use in the water sector, can offer a promising added layer of verification and transparency at low cost and with increasing reliability with the inclusion of newly collected data.

Information disclosure is a vital part of the policy mix. In contexts in which there is significant uncertainty, information has high economic value. As analysis in this report suggests, there is considerable uncertainty about the safe thresholds of key water pollutants that are pervasive across the world. In such circumstances, the provision of clear and understandable guidelines about the existing evidence and uncertainties involved would equip consumers with the ability to make better choices. One of the most powerful outcomes of information disclosure is its ability to inspire social movements and create the support needed for policy improvements. Citizens cannot act if they are uninformed or unaware of the situation. Encouraging and enabling this information is fundamental to the social contract that exists between the governed and the governors and is critical to getting this wicked problem under control.

Measurement is only effective if it is coupled with well-designed regulations that provide incentives for firms and individuals to adhere to water quality guidelines. But the longer the pipeline of regulations, the greater the opportunities for leakage, rent seeking, and corruption.

FIGURE ES.2: Ladder of Policy Interventions

	Passive		Proactive		Reactive	
	Information		**Prevention**		**Investments**	
	Trans-parency	**Monitoring systems**	**Enforce-ment**	**Legislative framework**	**Financing**	**Treatment**
STAGE ONE	Publish data online and in regional/global data-bases, as well as in schools and health centers	Establish water quality monitoring for major water sources (surface and groundwater)	Codified laws and regulations in place that incentivize the reduction of point and nonpoint source water pollution with clear jurisdictions for enforcement and sufficient levels of devoted resources		Treatment is publicly financed	100% of drinking water is treated (SDG 6.1.1)
STAGE TWO	Overlapping systems with remote sensing or alternative monitoring infrastructure	Systemati-cally monitor water quality in all sources of surface and ground-water	Smart contracts and automatic monitoring	Command and control structure	Incentives are put in place to attract private sector investors	100% of wastewater is safely managed (SDG 6.2.1)
STAGE THREE	Third-party or disaggregated publishing and verifica-tion system such as blockchain	Remote sensing or overlapping systems and early warning	Costs of water pollu-tion are fully internalized by polluters	Economic incentives (taxes, permits, payment for services schemes, etc.)	Treatment is financed through a blend of private sector financing and tariffs levied on polluters	Tertiary treatment of drinking and wastewater for denitrifi-cation

Hence, implementation deficits are especially large in developing countries with limited regulatory capacity. Fortunately, new technologies can be harnessed to improve enforcement in these circumstances. For instance, smart contracts—rules written in computer code that are embedded in a blockchain and automatically execute when the conditions are met—could be used to automatically enforce payments from polluters. Such automatic execution adds a level of transparency that is often missing in enforcement. For prevention to be effective, the monitoring system needs to be tamper proof, and it should not be possible to evade the sanctions for violations. With appropriate attention to incentives and design, such systems can galvanize polluters into action.

Long-standing assumptions about wastewater treatment infrastructure need to change—investments must be scaled up but also need to become more effective. More than 80 percent of the world's wastewater—and more than 95 percent in some developing countries—is still released into the environment without treatment. There is therefore an urgent need for greater investment in wastewater treatment plants, especially in heavily populated areas. But this report finds that at times, investments in wastewater treatment facilities lead to little measurable improvement in water quality, representing a waste of scarce public funds. The clear implication is that investments need to be accompanied by appropriate incentive structures that monitor performance, penalize profligacy, and reward success. Moreover, the large gap in public sector resources suggests the need for new models that attract private investments.

Finally, better land use policies and smart spatial planning are critical for protecting water supplies. Forests and wetlands act as natural buffers that absorb excessive nutrients that would otherwise pollute waterways. This report finds that globally, land extensification—from both urban expansion and agricultural land expansion—is one of the biggest threats to environmental water quality. It sharply increases the risk of hypoxia and anoxia (dead zones), which is a great threat to ecosystems and human health alike. Land use policies that preserve critical forests, wetlands, and natural biomass, particularly in the vicinity of high-value water resources, are therefore key to protecting water supplies.

Action is needed: water quality needs to be politically prioritized, and it should be treated as an urgent concern for public health, the economy, and ecosystems. The findings from this report show that long-term costs have been underestimated and underappreciated. The threats that poor water quality presents are largely imperceptible, and as a result, policy inaction and procrastination are often convenient responses to an invisible problem. But this means that populations are subjected to hazards without their knowledge or their consent. With water scarcity expected to increase as populations grow and the climate changes, the world cannot afford to waste and contaminate its precious water resources.

CHAPTER ONE

UNSEEN THREATS AND UNKNOWN COSTS

Like the constant dripping of water that in turn wears away the hardest stone, this birth-to-death contact with dangerous chemicals may in the end prove disastrous.

—Rachel Carson, *Silent Spring*

Throughout recorded history, humans have wrestled with water quality challenges. Around 500 BCE, Hippocrates, the father of modern medicine, observed that water transported in the aqueducts of ancient Greece had unpleasant odors and taste. Linking impure water to disease, he invented the "Hippocratic sleeve," one of the earliest water filters (Yfantis 2017). Industrial water regulations date back at least 800 years to the Kingdom of Sicily. There, the Constitutions of Melfi prohibited the soaking of flax and hemp in rivers within a mile of towns, because it was known that they emit toxins and pollute the drinking water. In addition, the link between cholera and poor water quality was firmly established by John Snow in the mid-nineteenth century. Rejecting the miasma theory of disease, Snow used statistical models to link cases of cholera to particular water stations in London, thus providing strong evidence that contaminated water was the source of the disease.

In more recent times, Rachel Carson's *Silent Spring* (1962) was a response to the proliferation of pesticides and chemicals that were carelessly dumped in waterways. Several years later, a fire on the Cuyahoga River in northeast Ohio, fueled by uncontrolled industrial dumping, led to the creation of the

The working papers showing full results as well as a technical appendix are available at www.worldbank.org/qualityunknown.

U.S. Environmental Protection Agency (EPA) and, shortly after, the passing of the Clean Water Act in the United States. In 2000, the European Union established the EU Water Framework Directive, recognizing the need for fundamental rethinking of how to manage Europe's water quality problems.

DON'T COUNT ON GROWING OUT OF IT

Despite this long history and knowledge of the impacts of water quality, the struggle to manage and contain the problem persists. Even high-income economies with well-resourced institutions find themselves unable to cope with the challenges. Four decades after the passing of the Clean Water Act and the Safe Drinking Water Act, more than 100,000 residents in Flint, Michigan, were exposed to lead in their drinking water. It required a national movement and three years for water to return to acceptable safety levels, but not before potentially thousands of children had been exposed to the harm caused by lead poisoning. In Europe, countries such as France, Germany, and Greece have been fined by the European Court of Justice for violating the regulatory limits for nitrates. Almost a third of monitoring stations in Germany present levels of nitrates exceeding the European Union's limits.[1] In Brittany, a northwestern region of France, runoff from livestock farms has caused nitrates in groundwater to reach sky-high levels, well beyond prescribed safe limits.[2] In England, river water quality lags behind peers with only 14 percent of rivers meeting the required minimum "good status" standard, according to a European Environment Agency (2018) report. In addition, threats posed by newly recognized pollutants such as microplastics and pharmaceuticals are poorly understood and, in many cases, unmanaged in countries rich and poor.

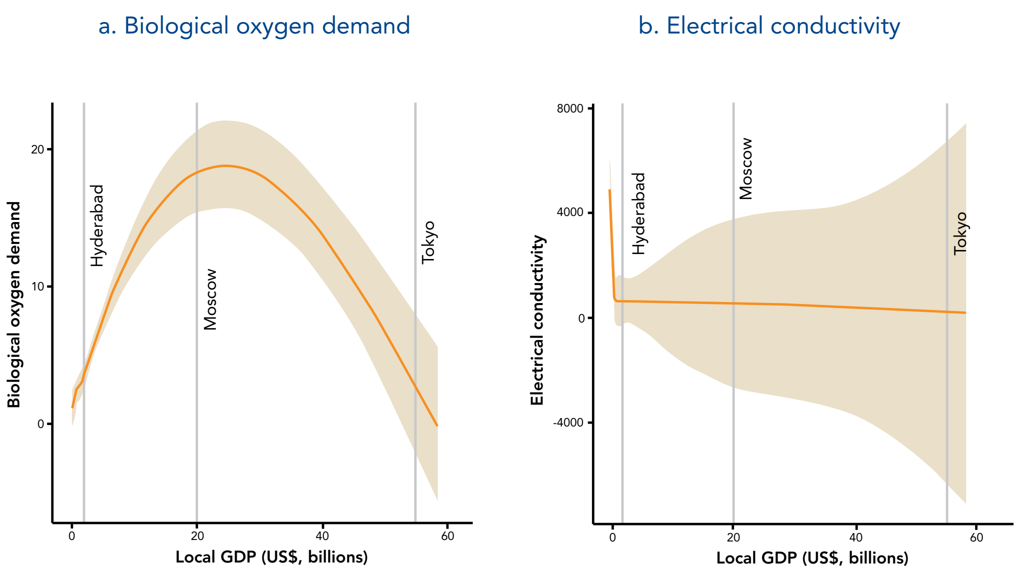
In the early 1990s, it was famously claimed by economists Gene Grossman and Alan Krueger that pollution would follow an inverted-U pattern with development. As countries grow and industrialize, pollution will increase. At some point, outrage from citizens or sufficient affluence would result in policies and cleaner technologies that cause the trend to reverse, with growth leading to a cleaner environment. This hypothesis, known as the environmental Kuznets curve, implies that growth is the best means to environmental improvement.

In some parts of the world, some parameters have followed an environmental Kuznets curve pattern. Panel a of figure 1.1 shows how biological oxygen demand (BOD) in water changes as one moves from poorer regions to wealthier regions. It appears to follow the pattern predicted by the environmental Kuznets curve. This is generally not caused by some natural law of economics. The main driving forces are environmental movements such as the one sparked by the Cuyahoga River fire, the work of conservationists and researchers like Rachel Carson, and large investments in infrastructure to monitor, regulate, and treat water. It is also important to note that the turnaround point at which BOD starts to decline is high, somewhere between cities with incomes the size of Moscow and Tokyo.

Although the environmental Kuznets curve may arise in certain situations and for certain pollutants, it unfortunately does not hold true generally. Other pollutants that are less visible or costlier to monitor and treat have shown little to no progress in developing and developed countries alike. As shown in panel b of figure 1.1, electrical conductivity (EC), an indicator of salinity in water, follows no such pattern. In addition, as is discussed in chapter 4, nitrates in surface water and gross domestic product (GDP) tend to rise together.

This is suggestive evidence that declining water quality is not a problem that a country can grow out of. Although free-market solutions exist and, in many cases, may be the most efficient means of controlling pollution levels, they rarely arise on their own. Even in wealthy countries whose regulatory capacities are high, public support for a cleaner environment is substantial, and a free and activist press holds businesses and politician accountable, tragedies such as the one in Flint, Michigan, still occur.

FIGURE 1.1: Relationship between Biological Oxygen Demand or Electrical Conductivity in Rivers and Local Gross Domestic Product



Sources: Water quality data are from the GEMStat database (see the book's appendix, available at www.worldbank.org/qualityunknown). Local gross domestic product (GDP) data are from Kummu, Taka, and Guillaume 2018.
Note: The lines trace the trend line between the two variables, and the shaded area is the 95 percent confidence interval. The relationship is determined through locally weighted scatterplot smoothing (LOWESS).

A major reason water pollution is so difficult to control is the dimensionality of the problem. Unlike air pollution, in which only a small handful of parameters need tracking, thousands of water quality parameters have been identified by organizations such as the World Health Organization (WHO). These span a wide spectrum, from nutrients, to salts, to chemicals, to bacteria and viruses, and they are measured through a variety of metrics, such as pH, EC, and dissolved oxygen. More problematically, the range of pollutants is ever increasing. In the United States alone, the EPA receives manufacturing notices for more than 1,000 new chemicals each year (EPA 2019). A mere decade or two ago, the world was oblivious to concerns from pharmaceutical drugs and microplastics in water supplies. It is just waking up to these concerns, and nobody knows what contaminants may be uncovered in the future.

As countries grow and develop, the cocktail of chemicals and vectors that they must contend with changes. Pollutants of poverty dominate poor countries with limited sanitation infrastructure and unimproved water sources and include fecal coliform, unmanaged geogenic pollutants, and general trash that clogs waterways. Pollutants of growing prosperity arise from industrial processes and intensive agriculture. Recently, the world is turning its attention to the harm caused by emerging pollutants, which include pharmaceuticals such as anti-inflammatory drugs, analgesics, antibiotics, and hormones, as well as plastics, which break down into microplastics and nanoplastics, emitting harmful chemicals and choking ecosystems.

It has been observed that traditionally, as levels of income increase, pollutants of poverty begin to disappear and are replaced with pollutants of growing prosperity and emerging pollutants. However, the rise of antimicrobial-resistant bacteria, antifungal-resistant fungi and amoebae, and drug-resistant macroparasites highlights a dangerous and growing interaction between emerging pollutants and sanitation-linked bacteria. If these problems are allowed to fester, we may see a delinking between economic growth and eradication of poor sanitation-related illnesses, trapping countries that are poor in a high disease environment.

Unsurprisingly, the visibility of the pollutant, or the effects that the pollutant has, usually determines how much priority it receives. Highly visible pollutants and pollutants with acute impacts, such as those related to fecal contamination, are often the first pollutants a country seeks to limit. Given their large, visible impacts, there is significant motivation to control these pollutants. Failure to do so often arises from financial constraints, although government capacity and cultural factors may also be important. Chemical pollutants whose impacts may take years to manifest in the form of cancer or other chronic illnesses receive less attention, as it is harder to directly link health impacts to exposure to specific pollutants in the past or over time. Pharmaceutical pollutants, hormones, and plastics have only recently gained attention because of growing recognition of the extent of the problem, but little is yet known about the potential health impacts.

This pattern of intervention perhaps has some economic merit. When considering severity, risk percentages, and time discounting, acute impacts are easier to identify and could have larger economic impacts. But interventions are also driven by political economy. Governments are more likely to be held accountable for risks over the short term, when links between pollution and health or economic impacts are more obvious. Little incentive exists for politicians with short time horizons to address pollutants that have longer-term consequences, particularly when contemporaneous economic costs of regulation are high.

IGNORANCE IS NOT BLISS

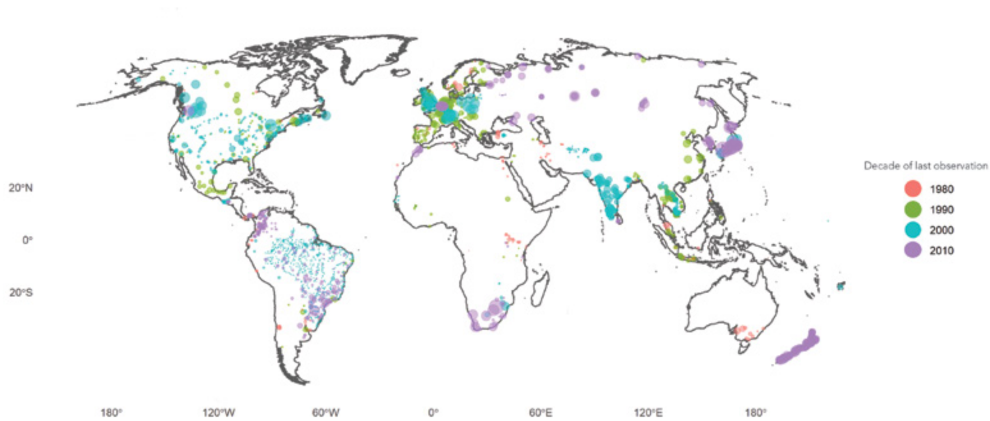
Avoiding the impacts of something that cannot be seen is difficult, and only better data can shed light on the issue. Therefore, monitoring and publishing data on water quality are crucial. Global water quality monitoring is severely lacking. Water quality data exist at the regional and national levels, but they are often sparse in space, time, and parameters collected and are often jealously guarded by authorities, providing little in the form of public benefits to citizens.

Three major types of water quality data exist: data from in situ monitoring stations or collected samples, data from remote sensing, and computer-generated data built from machine learning models. All of these sources were used in this report and are discussed next. More in-depth information is provided in the appendix.[3]

DATA FROM MONITORING STATIONS

There is one global repository for water quality data, GEMStat, which is hosted by the United Nations Environment Programme (UNEP). GEMStat contains more than 3.3 million observations of water quality (at the time of publishing) from 72 countries, some dating back to the 1960s, for 224 parameters. Although this database has been vital for researchers and policy makers, it has limitations: it is self-reported, and as a result, both the parameters collected and the frequency of collection are sporadic across and within countries. Coverage is also sparse in some regions. Map 1.1 shows station locations in the GEMStat database. Dot colors show the decade of the most recent observation from each station. As can be seen, nearly all of Africa is unrepresented after 2000, as well as large parts of Central Asia, the Middle East, China, and southern and western South America. To accompany this data set, several other national or basin-level data sets were collected, which are detailed in the online appendix.

MAP 1.1: Station Locations in the GEMStat Database



Source: GEMStat database.
Note: Each dot represents a station in the GEMStat database, aggregating across all water quality parameters. The size of the dot increases with the number of observations available, and the color indicates the decade of the most recent observation.

DATA FROM THE SKY

Remote sensing of water quality from satellite imagery or drones is a relatively new technique that is becoming more widespread and increasing in accuracy. Medium- to high-resolution and high-frequency satellites such as Envisat MERIS or Sentinel allow for Earth observations and data collection. Recently, models have become more accurate in predicting certain water quality parameters by comparing them with in situ observations to establish a relationship between satellite data and water quality. Remotely sensed water quality data have several benefits over station data: they are automatically captured by satellite, eliminating reliance on river or lake monitoring stations; they are tamperproof, preventing vested interests from modifying results; and they can show spatial variation in a lake or river rather than collecting water quality data at a single point, which may be misleading.

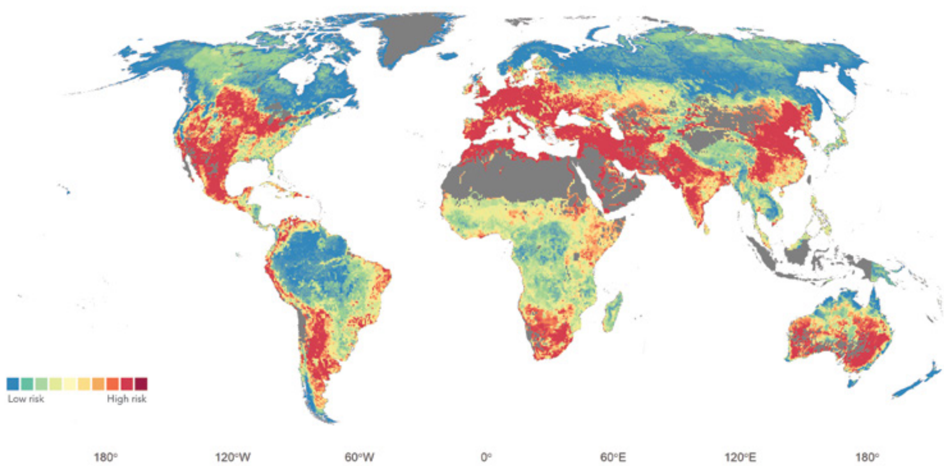
Nevertheless, remote sensing is unlikely to offer a panacea. The observed parameters are mainly restricted to environmental parameters, such as chlorophyll, total suspended solids, turbidity, floating vegetation, colorized dissolved organic matter, and temperature. Chemical and bacterial parameters are not visible to satellites, because they generally do not cause distinguishable changes in the spectrums observed by satellites. In addition, the water body being observed needs to be of sufficient size or width for enough pixels to be captured for analysis. As new satellites with higher resolutions come online, detection of water quality in smaller lakes is becoming possible, and new algorithms are being developed to detect water quality in rivers. For this report, one of the largest historical water quality databases in lakes was produced. Analysis of these data is discussed in more detail in the online appendix.

DATA FROM MACHINES

When data from neither in situ observations nor satellites are available in the desired locations or at the required times, simulated data from hydrological models have been used. The factors that determine water quality are fairly well known. Models that estimate risks of poor water quality at a global scale are gaining more traction in the scientific and international community to fill existing gaps in available data.

This report explores a new avenue to derive such models: machine learning. By combining data on water quality determinants with the in situ observations that do exist, machine learning algorithms are able to find patterns that would otherwise go undetected. Several machine learning data sets have been produced for this report, including for BOD, nitrogen, and EC. Altogether, these data sets can give a clearer understanding of the areas around the world that are at risk from poor water quality—from fast-growing Asia to the richest regions of the world. Map 1.2 displays a risk map constructed from these data. It represents the interaction among risks from BOD, salinity, and nitrogen pollution.

MAP 1.2: Global Risk of Poor Water Quality



Note: This map shows a water quality index summarizing global predictions for biological oxygen demand, electrical conductivity, and nitrogen. Each value is scaled to a common support for comparability and then summed together. Average values for 2000–10 are displayed. Gray areas have no data for one or more parameters. More details on the construction of the index are presented in the appendix (available at www.worldbank.org/qualityunknown).

HOW MUCH DOES IT COST?

Another impediment to effectively and efficiently controlling water pollution is a lack of well-established dose-response functions that describe how pollution affects outcomes of interest, such as health and economic impacts. Organizations such as WHO and the EPA have established safe concentration levels for many of the most common pollutants. Although these concentration levels are partially based on the latest science, there is great uncertainty about the true safe value. For instance, the EPA sets the limit for nitrate-nitrogen in drinking water at 10 milligrams per liter (mg/L).[4] However, there is emerging evidence, including from new results in this report, that this threshold may be too high (Schullehner et al. 2018). That such uncertainty exists around nitrates, one of the most common, well-known, and regulated pollutants, speaks to how difficult it is to get the safe levels right.

Economic growth and water pollution are intrinsically linked. Nearly all forms of production create pollution as a by-product. Because water is needed for life, health, and economic production, the impurities generated by upstream polluters may affect downstream users.

With the understanding that eliminating all water pollution is too costly and infeasible, regulators and policy makers must make decisions about the appropriate level of water pollution. In strictly economic terms, this calls for weighing the benefits from the polluting activity against the costs of pollution. Because both benefits and costs derive from the same source, isolating and quantifying the macroeconomic impacts of each is challenging. A naïve approach that correlates water pollution to GDP will likely conflate the positive and negative impacts. To eliminate the bias associated with the naïve approach, this report uses an identification strategy that isolates positive and negative consequences: Because pollution flows downstream, the bulk of benefits are attained in the region where the pollution is generated, whereas adverse impacts will be concentrated downstream from the source of pollution (box 1.1).

Is it possible to determine the total economic cost that bad water quality has on economic activity? Given the complexity of the issue and the wide-ranging effects, some of which are acute and contemporaneous while others are long term and slow moving, that question remains unanswered. However, using the methodology described in box 1.1, it is possible to generate an indication of the relationship between upstream water quality and downstream economic activity.

Although there are many water quality parameters to choose from, BOD seems most suitable for this analysis. BOD measures the amount of oxygen required to break down organic material. Its near-universal availability (at least in regions where water quality monitoring exists), combined with its ability to proxy different kinds of pollutants and the general environmental quality of water, make it a useful proxy indicator of overall water quality. To analyze the economic impact of BOD, upstream monitoring stations are matched to downstream levels of local GDP. Rather than relying on country-level values

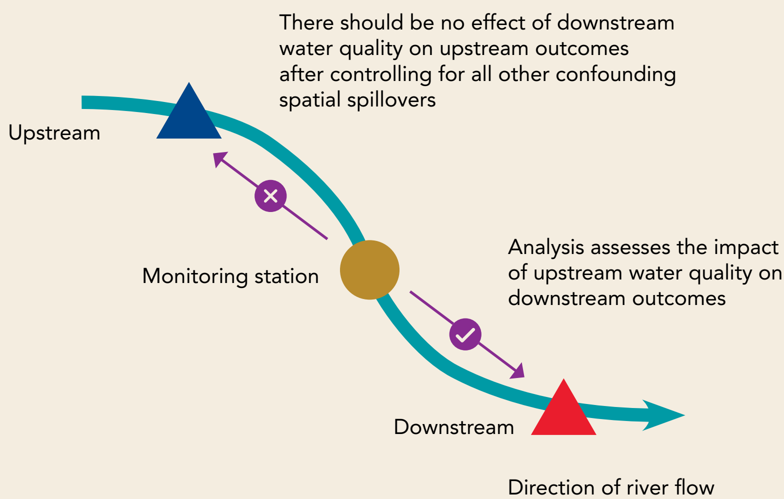
BOX 1.1: Accounting for Streamflow

As described in the main text, there is a circular relationship between water pollution and economic growth. Nearly all growth generates some by-product, and that by-product is often discharged into waterways or soils, which eventually finds its way into larger rivers. At the same time, the presence of water pollution undoubtedly impacts economic activity—whether through increasing health costs, reducing labor productivity, raising costs for businesses, or reducing agricultural yields. This two-way relationship makes establishing causal impacts between economic activity and water pollution challenging.

Nevertheless, as is common in the literature, it is possible to use strategies that separate the negative and the positive effects by taking account of the fact that water flows downstream. The benefits to higher levels of production largely accrue upstream, whereas the costs that are imposed by water pollution are felt in downstream regions. To determine the impacts of water quality on economic activity, digital elevation models are used to link water quality to downstream regions.

This is demonstrated here pictorially. In figure B1.1.1, water quality measured at a particular location (gold dot) should impact downstream users (red triangle), but not those upstream of the source of pollution (blue triangle), after accounting for all other confounding factors. The latter can serve as a falsification test to examine the robustness of the identification strategy.

FIGURE B1.1.1: Using Streamflow Direction to Identify Impacts of Water Quality



that blur the picture by averaging over large areas, local GDP is employed, using a new data set that disaggregates GDP into small grid cells. Other confounding factors are controlled to isolate the impact of BOD (see box 1.2 for more details on the data used and the empirical setup).

The results are striking, if not surprising. When the BOD level exceeds 8 mg/L—a level at which rivers are considered heavily polluted—GDP growth falls significantly, by 0.82 percentage points, in downstream regions. This is compared with a mean growth rate of 2.33 percent, implying that around a third of growth is lost. When the sample is restricted to only middle-income countries, where BOD is a bigger problem, the impact increases to 1.16 percentage points, implying that almost half of growth is lost. In high-income countries, where levels of BOD are lower, GDP only declines by 0.34 percentage points in regions downstream of heavily polluted rivers.

To test for robustness of results, several alternative specifications were estimated using similar setups. One reasonable approach is to explore whether GDP impacts decline systematically with lower levels of BOD pollution. If they do not, this would suggest that some excluded factor could be accounting for this result. When using alternative thresholds for BOD level, it is found that impacts scale with the level of BOD. For instance,

BOX 1.2: Estimating the Impact of Upstream Biological Oxygen Demand on Downstream Gross Domestic Product

To estimate the impact of increasing levels of biological oxygen demand (BOD) on downstream economic activity, a panel regression is estimated. The world is split into grid cells measuring 0.5 degrees on each side, which is approximately 50 by 50 kilometers at the equator. Local gross domestic product (GDP) data are collected from Kummu, Taka, and Guillaume (2018). Using a digital elevation model, grid cells are matched to the nearest upstream water quality monitoring station with data on BOD. If no monitoring station exists within 100 kilometers, then the grid cell is dropped from the analysis.

Other factors that are known to impact GDP growth are added as a set of controls. These include weather variables (quadratic forms of yearly averages of temperature and rainfall) and population (Matsuura and Willmott 2012a, 2012b). Year-fixed effects capture common time-varying factors, grid cell–fixed effects capture time invariant factors like geography, and month of water quality observation–fixed effects control for intraannual variations in water quality. Finally, country-specific time trends capture economic transitions that are occurring within countries. All of these controls, fixed effects, and time trends attempt to isolate other factors that are correlated with BOD and may be contributing to changes in GDP. By including them, they purge variation that may confound the result and allow the direct impact of upstream BOD on downstream GDP growth to be captured.

losses in GDP growth are 25 percent higher downstream from heavily polluted rivers (BOD > 8 mg/L) than from moderately polluted rivers (BOD between 2 and 8 mg/L). In addition, when growth in GDP is replaced with growth in GDP per capita, results remain consistent, implying that shifts in population are not driving the results. Results from these specifications and others are available in the report's appendix, as well as in background papers.

These results are likely to be underestimates of the true impact. Examining downstream regions isolates the negative externalities of water pollution and partially excludes the benefits of the economic growth that generated them. However, all growth, particularly when it occurs within the same country, is intrinsically linked. It is therefore likely that downstream regions still see a spillover of economic benefits from upstream production, thus biasing the estimates toward zero. The implication is that this result is likely an underestimate of the true impact.

Although these results provide striking summary evidence of the economic consequences of deteriorating water quality, several shortcomings of this analysis must be noted. First, the data on local GDP are novel and important but also imperfect. Globally, data on economic activity are only available at the country level and, for some countries, at the province or state level. Data sets like the one employed collect as much subnational data as is available and then rely on algorithms to distribute these data into grid cells. Although the techniques for distributing these data are logical, they are imperfect and may contain systematic errors. The use of BOD as a proxy for overall water quality also has its shortcomings. Although BOD is an important parameter for measuring the health of a water body, it does not provide information about the specific pollutant causing the changes in BOD or the source of the pollutant. In one region, for instance, industrial chemicals may be causing spikes in BOD, whereas in another region, bacterial contamination may be the source. These different types of pollutants will have different health, environmental, agricultural, and industrial impacts, which will translate into different overall economic impacts. These different impacts end up amalgamated into a single, overall average impact in the regression.

SUNLIGHT IS THE BEST DISINFECTANT

The preceding results are not an end in themselves; they only represent the continuation of an important line of research on global impacts of poor water quality. Future research should aim to disentangle impacts of different pollutants and their impacts on different sectors. In part, that is the goal of the remainder of this report. In the chapters that follow, this report drills down into the different sectors that water quality impacts and presents findings from new research into the microeconomic impacts of water pollution Where appropriate, this new research is presented alongside existing literature to better contextualize it and provide additional background and information.

Although many water quality parameters were considered for inclusion, the report ultimately focuses on pollutants and proxies that have also been identified by the UNEP and the global community in the Sustainable Development Goals (SDGs) as among the most critical for surface water quality. These parameters include dissolved oxygen, nitrogen, phosphorus, EC, and pH, which are tracked as part of the indicator SDG 6.3.2 (proportion of bodies of water with good ambient water quality). However, given the overlapping nature of many of these pollutants, the focus is on three representative parameters: BOD, which is an umbrella proxy of river health; nitrogen to capture the nutrient explosion in water bodies; and salt balance in water captured through EC:

- BOD is one of the most widely used water quality indicators. It is a measure of the amount of oxygen that bacteria will consume in decomposing organic matter (Barnes, Meyer, and Freeman 1998). Therefore, it is often used as an umbrella proxy for overall water quality. It is highly correlated with other water quality indicators, such as dissolved oxygen and chemical oxygen demand, and is a good indicator of the amount of organic material in water.

- Nitrogen is an outlier pollutant in terms of scale, scope, trends, and impacts. It is possibly the largest global externality, rivaling carbon. In water, it can manifest as nitrate, nitrite, and ammonium nitrate, among other compounds, all of which are harmful for human health and ecosystems when present in sufficient concentrations. Although some impacts are well known, others are poorly understood. As will be discussed in chapter 4, its use as a nutrient is highly correlated with phosphorus, although the harmful health effects from consuming it in its oxidized states are better established.

- EC is directly related to the concentration of dissolved solids in the water. It is therefore a widely used proxy for salinity, which also correlates highly with pH. This is perhaps the world's oldest and most widespread pollutant. Salt can be both a pollutant of poverty, caused by climate change, sea level rise, and geogenic factors, and a pollutant of prosperity, caused by overextraction of water and irrigated agriculture. Saline water can be disastrous for both agriculture and human health, particularly of young children.

These pollutants are by no means the only important contaminants for countries to track and control. Bacterial contamination from poor sanitation coverage; heavy metals like arsenic, fluoride, and lead (box 1.3); persistent organic pollutants such as DDT and industrial pollutants; and a range of others also pose large health and economic risks. However, in many ways, the pollutants tracked by SDG 6.3 represent the least common denominator of water pollutants. They are problematic in regions rich and poor, wet and dry, and urban and rural.

BOX 1.3: Health Impacts of Heavy Metals in Drinking Water

Heavy metals can enter drinking water in various ways. Geogenic pollutants such as arsenic occur naturally. Arsenic is most widespread in arid and semiarid basins, volcanogenic areas, and aquifers in alluvial sedimentary rock (Nordstrom 2002). It is most famously problematic in Bangladesh and West Bengal, India, where millions of people have been exposed to arsenic poisoning through groundwater. Argentina and northern Chile form another global hotspot, where mining activities have dislodged arsenic deposits and exacerbated water supply contamination (see annex 2A). Acute impacts of arsenic exposure include vomiting, abdominal pain, diarrhea, and death. Long-term impacts include skin lesions and pigmentation changes and cancers of the skin, bladder, and lungs.

Another common geogenic water pollutant is fluoride, which often cooccurs with arsenic. Fluoride occurs in natural water sourced worldwide, with high concentrations found throughout Central Asia, the Middle East, and northern, east, and southern Africa, with significant high concentrations in Argentina, Australia, Mexico, the Russian Federation, and the western United States (Amini et al. 2008). It is estimated that fluoride exposure from drinking water impacts 200 million people in 25 countries, with 66 million people affected in India alone (Ayoob and Gupta 2006). Fluoride exposure can cause dental and skeletal fluorosis in humans, which can lead to chronic pain and damage to joints and bones (Fawell et al. 2006).

Mercury is another dangerous metal that occurs naturally in some locations, but it is also often a by-product of artisanal gold mining, where it is used to separate gold from sediment. Acute ingestion of mercury can have devastating health impacts, including cardiovascular system collapse, renal failure shock, and gastrointestinal damage (WHO 2005).

Other heavy metals, such as lead, aluminum, copper, cadmium, and zinc, often make their way into drinking water supplies through aging and corroding pipes and pipe fittings. One of the most acute recent examples of this was in Flint, Michigan, when in 2014 the city changed its drinking water source from Lake Huron to the Flint River while failing to apply needed corrosion inhibitors to the water. The more acidic water supply corroded the lead pipes and exposed residents to lead-contaminated water. Lead exposure in children can cause neurodevelopmental impacts, reducing IQ and future productivity. Globally, it is estimated that the burden associated with childhood lead exposure amounted to 1.2 percent of the GDP in 2011 (Attina and Trasande 2013), though much of this exposure is also coming from other environmental sources, like air pollution and soil and food contamination.

STRUCTURE OF THE REPORT

Although no report on the economic impacts of water quality could be truly comprehensive, given the wide-ranging scale, scope, and impacts of the problem, this report attempts to highlight the major impacts of poor surface water quality, describe the challenges associated with them, and offer prescriptions for reducing them. In the chapters that follow, new analyses, methods, and data sets are described alongside reviews of the existing literature.

Chapter 2 examines the impacts that the preceding pollutants have on health, productivity, and human capital. For much of the developing world, the focus is on improving sanitation and reducing health impacts caused by fecal coliform and other bacteria. Although this problem is far from solved, other harmful pollutants are urgently in need of attention. The chapter describes new findings on the costly impacts of nitrogen and salinity in water, which shows that health effects may be larger, longer lasting, and occurring at lower levels than previously thought. An annex to the chapter discusses impacts of arsenic, an important water pollutant.

Chapter 3 focuses on the relationship between agriculture and water pollution. Although it is well known that saline water harms agricultural productivity, the extent of the problem has yet to be systematically measured. This chapter demonstrates that saline waters are causing significant declines in food production in developed and developing countries alike. With climate change, this is a problem that is set to worsen. It also highlights the invisible crisis of food quality that exists throughout the developing world when agriculture is irrigated with untreated wastewater.

Chapter 4 describes some environmental impacts of poor water quality. Algal blooms, fish kills, and hypoxia often make big headlines when they occur in wealthy or populous regions. Using one of the largest databases on water quality in lakes yet assembled, this chapter sheds light on how widespread the problem is and identifies the major drivers at a global scale.

Chapter 5 explores what are considered emerging pollutants: pharmaceutical drugs and microplastics. The potential dangers of these pollutants have only recently caught the attention of the global community. Although some hazards associated with them have been identified, chiefly the spread of antimicrobial resistance, impacts on human health and the environment remain an unfortunate blind spot.

Finally, chapter 6 builds on the results, analysis, and literature of this report and attempts to provide insight into solving the wicked problem of managing water quality effectively and efficiently.

An appendix to this report goes into more detail on the data employed, technical details of all analyses in the report, and several analyses that are congruent to the report's findings.

NOTES

1. Germany was consequently fined in 2018: case C-543/16.
2. Based on data from Accès aux Données sur les Eaux Souterraines (ADES), https://ades.eaufrance.fr/. See also https://www.ecosurvey.it/en/2014/09/eu-court-of-justice-against-france-for-violation-of-the-nitrates-directive/.
3. www.worldbank.org/qualityunknown.
4. This is equivalent to 44.3 mg/L as nitrate which is approximately equivalent to the WHO guideline of 50.0 mg/L as nitrate (corresponding to 11.3 mg/L nitrate-nitrogen).

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CHAPTER TWO

HEALTHY, WEALTHY, AND WISE

It ain't what you don't know that gets you into trouble. It's what you know for sure that just ain't so.

—attributed to Mark Twain

KEY POINTS

- The focus of this chapter is mainly, but not exclusively, on the water quality parameters identified and targeted in Sustainable Development Goal (SDG) 6.3. The chapter also summarizes the vast body of literature that focuses on poor sanitation and hygiene tracked in SDG 6.2, and its related impacts.
- There is still uncertainty regarding prescribed safe limits of water quality parameters, the timing of impacts (whether acute or chronic), and the range of health effects.
- New research presented in the chapter finds that exposure to nitrogen pollution can not only be fatal but also impair the healthy growth of children and their later-life earning potential. Exposure to saline water can cause adverse birth outcomes at levels far below prescribed limits and even in regions with lower levels of contamination.
- The multiple dimensions of uncertainty mean that the scale of the water quality problem is still largely unknown, even for pollutants that are widely monitored and regulated.

The aim of this chapter is to explore the health consequences of water pollution. The focus is mainly, but not exclusively, on a core set of water quality parameters that have been identified as priority pollutants in the Sustainable Development Goals (SDGs). SDG 6.2 is concerned mainly with inadequate sanitation and the health impacts caused by excreta- and water-related disease transmission. These have been comprehensively investigated, so they are only covered briefly in this chapter. SDG 6.3 has a wider remit and identifies pollution from nutrients (measured through nitrogen and phosphorous), because these have known effects on both the environment and human health; salts (measured through pH and electrical conductivity), for their effects on agricultural productivity and health; and dissolved oxygen, which provides an umbrella proxy for the overall health of a water body. The effects of these parameters on human health are less understood than those of sanitation-related contaminants and thus take center stage in this chapter.

The findings suggest that the health effects of these water quality parameters are larger and more uncertain than has been recognized, serving as a timely reminder that actions taken so far to control water pollution have yielded limited results. Many developing countries endure not only the pollutants of poverty identified in SDG 6.2 but also the consequences of the pollutants identified in SDG 6.3, creating a double burden in urgent need of attention. Technical details of all results are relegated to the appendix.[1]

FROM TOILET TO TAP: WATER QUALITY AND SDG 6.2

Safely managed sanitation is essential to protecting the health of individuals, communities, and the environment. Open defecation, leaking latrines, and raw wastewater can spread disease, provide a breeding ground for mosquitoes, and pollute groundwater and surface water that may serve as potential sources of drinking water. Cholera, an acute diarrheal disease linked to water with fecal contaminants, can kill within hours if untreated and infects up to 4 million people each year, killing an estimated 21,000 to 143,000 people (Ali et al. 2015). The 2017 report of The Lancet Commission on pollution and health estimates the number of deaths associated with sanitation-related water pollution at 0.8 million (Landrigan et al. 2017). Tragically, around 60 percent of diarrheal deaths of children under five years still result from inadequate drinking water supply, sanitation, and hygiene (WASH) behaviors (Prüss-Ustün et al., forthcoming). Millions of others who are spared this death sentence suffer scars that persist throughout their lives, locking them into an irreversible course of poor health, strained learning, and low productivity (box 2.1). This is why SDG 6.2 aims for the universal provision of adequate sanitation and an end to open defecation. Between 1990 and 2015, sanitation improvements have accounted for just under 10 percent of the decline in child mortality (Headey and Palloni 2019). Even though there has been progress, achieving this ambitious goal remains a fundamental challenge in many parts of the developing world.

BOX 2.1: Adverse Effects of Water Pollution: Irreversible Scars through Life

It is well established that deprivations and exposure to harmful conditions in utero or in the early years of life have lasting consequences that can impede human development. This is because a developing fetus, infant, or young child is sensitive to a host of environmental factors that can impair development and play a significant role in shaping adult outcomes (Barker 1990). This has been shown repeatedly in both the economic and the medical literature and is often called the fetal origins hypothesis (Almond and Currie 2011; Almond, Currie, and Duque 2018).

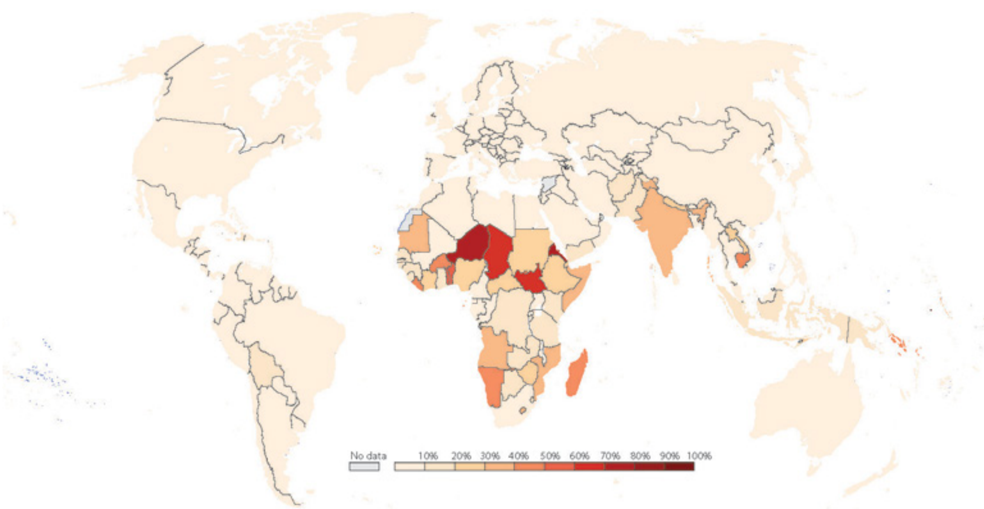
A host of water- and excreta-related diseases contribute to higher rates of undernutrition, anemia, and inflammation—conditions that impair cognitive functioning and physical development in children and whose impacts can be long lasting. The accumulation of these conditions throughout childhood often results in the physical marker of stunting, which occurs when a child is more than two standard deviations below the reference height for the age cohort. Although stunting is the visible indicator of an unhealthy environment during the prenatal, infant, and early childhood years, the less visible effects are often greater. Stunting can have severe consequences for cognitive development, overall health, and even socioeconomic conditions that carry into adulthood.

Stunting is generally caused by lack of nutrition, which prevents the body from developing to its potential. This could be the result of consuming too few macro- and micronutrients or exposure to an adverse disease environment, especially diarrheal diseases that prevent the body from absorbing nutrients that are consumed. A plethora of water- and excreta-related diseases affect the gastrointestinal tract and can give rise to diarrheal diseases. As a result, poor sanitation and poor water quality are the second and third leading risk factors for stunting worldwide, with a combined 13 million cases in 137 developing countries (Danaei et al. 2016).

As a child moves through adolescence, these impacts cascade beyond health, showing up through low rates of school attendance and poor academic performance. In adulthood, this eventually translates into low human capital, productivity, and wages (Lawson and Spears 2016). If there is further exposure to poor water quality and unhygienic sanitary conditions in adulthood, the burden of morbidity and mortality rises above baseline levels. Where the burden is high, repeated illnesses for family members can further trap households in a poverty cycle. The impacts of water pollution can thus cause scars that run deep and wide throughout life.

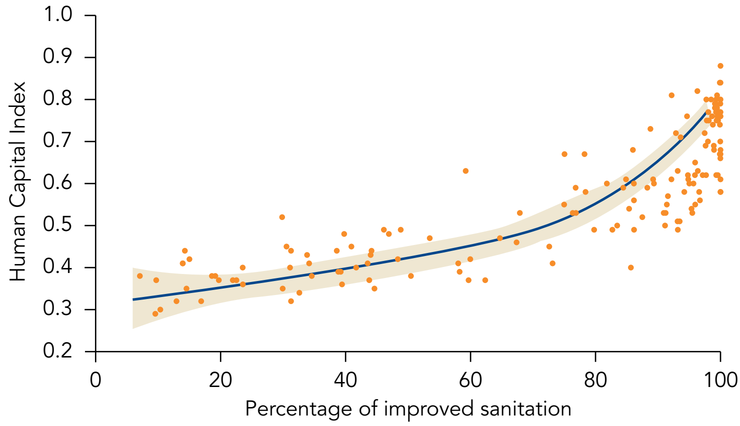
More than 1 billion people around the world still do not have basic sanitation facilities such as toilets or latrines. Of these, 892 million defecate in the open (WHO/UNICEF 2017) (map 2.1).[2] A large body of evidence suggests that poor sanitation is associated with a host of health problems including diarrhea, gut impairment, chronic intestinal disease, worm and parasite infections, and environmental enteric dysfunction (Prendergast and Kelly 2012). Poor sanitation can affect children long before they are born. Women exposed to poor sanitary environments are at higher risks of experiencing preterm birth and low infant birthweight (Baker et al. 2018; Padhi et al. 2015), both important predictors of stunting later in childhood (Christian et al. 2013). Clearly, there are compelling reasons to address this challenge. There is a conspicuous link between access to improved sanitation and the World Bank's Human Capital Index—a metric of a country's efficiency in developing human capital and its forgone development potential (Gatti et al. 2018) (figure 2.1). Although figure 2.1 does not imply a causal relationship, it illustrates the effect that improved sanitation has on human development outcomes. It shows that as sanitation improves, the Human Capital Index also increases. Although none of the indicators that comprise the Human Capital Index, such as health and education, explicitly include water and sanitation, the graph suggests that sanitation underlies and impacts them all.

MAP 2.1: People Practicing Open Defecation, Percentage of Population, 2015



Sources: Ritchie and Roser 2019; WHO/UNICEF Joint Monitoring Programme for Water Supply and Sanitation.

FIGURE 2.1: Improved Sanitation and the Human Capital Index



Sources: Gatti et al. 2018. Data on improved sanitation are from https://washdata.org/.
Note: Each dot signifies a country included in the Human Capital Index of the World Bank Human Capital Project.

A well-established body of research shows why sanitation matters for human capital formation. Research links open defecation to lower height-for-age scores in children across a range of countries, including Bangladesh, Cambodia, Ethiopia, India, Indonesia, and Mali (Spears, forthcoming).[3] The impacts are particularly severe in areas with high population density, such as India (Hathi et al. 2017), where cross-contamination is more likely. Remarkably, sanitation appears to be the key determinant of stunting globally, accounting for close to 54 percent of the variation in average child height (after controlling for wealth, genetics, and other coincidental differences), with gross domestic product (GDP) only explaining 29 percent of height differences (Spears 2013). It is therefore not surprising that reducing exposure to fecal contaminants leads to improvements in health (Pickering et al. 2015). Stunted growth matters, because it is correlated with the cognitive development of children, ultimately leading to lower levels of education and human capital.

A plethora of other studies have linked improved water and sanitation to better academic achievement. Indian children who experience better sanitary conditions in their first year of life also have improved cognitive achievement scores later in life, including better ability to recognize simple letters and numbers by the age of six years (Spears and Lamba 2016). Improved access to sanitation facilities has also been shown to increase enrollment in primary schools in India (Adukia 2017) and rates of school completion in Brazil (Ortiz-Correa, Resende Filho, and Dinar 2016). In Mexico, a major water reform program—Programa de Agua Limpia (Clean Water Program)—disinfected previously untreated water supplies. This led to significantly improved academic achievement in treated areas for those who were infants during the time of treatment (Bhalotra and Venkataramani 2013).

Though the threats of poor WASH are still great, these tend to gradually decrease as economies develop and invest in improved infrastructure, the proper containment of waste, and its safe conveyance, treatment, and disposal. Nevertheless, the threat of water pollution from other contaminants does not necessarily decline with prosperity and growth.

NITROGEN POLLUTION: BREAD FROM AIR OR TOXIC PLUMES?

At the start of the twentieth century, the German scientists Fritz Haber and Carl Bosch made a far-reaching discovery—the transformation of "air into bread" or *brot aus luft*. The scientists invented a process for converting atmospheric nitrogen from the air into ammonia, a form of reactive nitrogen, which is also a synthetic fertilizer for plants (Harford 2017).

This discovery earned the scientists a Nobel Prize as it transformed agriculture, led to a dramatic increase in yields, and supported the lives of several billion people who otherwise would have died prematurely or never been born (Erisman et al. 2008; Stewart et al. 2005). As a result, there has been a rapid increase in the use of synthetic nitrogen fertilizer the world over (see chapter 4).

But often, much of the nitrogen that is applied as a fertilizer eventually enters rivers, lakes, and oceans, fertilizing blooms of algae that deplete oxygen, creating hypoxic or dead zones where little can survive. Even though the dominant source of nitrogen pollution in the water is the agricultural sector, other diverse sources, such as human waste and untreated wastewater, also contribute to its proliferation. As cities grow and become denser, the threats of nitrogen leaching from belowground septic tanks, human sewage, urban wastewater, and urban stormwater runoff are expanding.

The fallout of nitrogen pollution is considered one of the most important environmental issues of the twenty-first century, and is one of the largest global externalities facing the world (Kanter 2018; Keeler et al. 2016). The world has likely surpassed the safe planetary boundary for nitrogen—a level of human interference beyond which environmental damage increases dramatically and possibly permanently (Steffen et al. 2015).

HEALTH LEGACY

It has long been known that ingestion of nitrates and nitrites can kill infants. When water with high levels of nitrate is consumed, it reduces the blood's ability to transport oxygen, causing the brain and body to shut down, and ultimately leads to infant death. Methemoglobinemia, popularly known as blue baby syndrome, was the initial trigger for the creation of drinking water standards for nitrates, set at 10 parts per million.[4] Nitrogen and its derivatives are also linked to significant increases in infant and neonatal mortality, particularly if exposure occurs during the month of conception. There is strong causal evidence from India, where the Green Revolution offers a natural context to study how consistent increases in nitrogen use have impacted infant deaths (Brainerd and Menon 2014).

An issue that has not been adequately explored is the fate of children who have survived consumption of high doses of nitrogen in their early years.[5] This is investigated in detail here across distinct geographies spanning India, Vietnam, and 33 countries in Africa.

The analysis is based on data from the Demographic and Health Surveys (DHS) in Africa and India, and the Living Standards Measurement Study in Vietnam. These surveys are combined with in situ river monitoring station data for India and Vietnam and predicted values of nitrate from a machine learning algorithm in Africa, following the methodology described in the appendix. These data sets are then used to investigate the relationship between early-life nitrate exposure and height measured as an adult (India), in childhood (Vietnam), and in infancy (Africa). Height reflects the accumulated effects of early-life health and diseases and is a well-known proxy for overall health and productivity. To credibly estimate the impacts of pollution exposure, the analysis exploits the direction of river flow and the upstream-downstream geographic relationship used in the literature (Do, Joshi, and Stolper 2018; Garg et al. 2018; Keiser and Shapiro 2018), following the methodology described in box 1.1 (see Zaveri et al., forthcoming, for technical details). Because the costs imposed by water pollution are largely felt in downstream regions, the analysis focuses on the impact of upstream pollution on health outcomes in downstream regions. To isolate the average pollution spillover at downstream locations, the analysis uses a rich set of controls. These are meant to control for time-invariant, location-specific characteristics such as local soil quality and natural resource endowment, as well as factors that vary by year and month, such as weather, and national trends in economic output and technological development. The analysis also controls for time-varying factors that are specific to regions to capture regional-level policies. Where possible, the analysis controls for other correlated water quality indicators such as fecal coliform, as well as individual, parent, and household-level characteristics depending on the sample of study. Lastly, to ensure that later-life health outcomes are measured in the same location of conception and birth where exposure occurred, the sample is restricted to individuals who have never migrated from their place of birth.

The analyses are undertaken over wide geographic areas and long periods, implying that the uncovered relationships are robust, not merely statistical artifacts. Even though direct measures of drinking water quality are unavailable, in situ monitoring data serve as reasonable proxies for levels of nitrates in drinking water. This is because nitrates are notoriously expensive and difficult to remove from water. Even in the United States, the percentage of public water systems that have violated safety limits for nitrates in drinking water has increased in the 15-year period between 1994 and 2009, a reflection of the challenges of coping with rising nitrate pollution (Ward et al. 2018). In other economies, including India, Japan, Lebanon, Morocco, Niger, Nigeria, Pakistan, the Philippines, Senegal, Turkey, and Gaza, nitrates in drinking water often cross conventional safety thresholds,[6] not only because of high concentrations in surface water bodies but also because of contamination of groundwater (box 2.2).

NITROGEN LEGACY IN INDIA

In India, the tremendous growth in food production that arrived with the Green Revolution in the mid-1960s was a watershed moment. It revived the languishing agricultural sector. But along with a rapid increase in agricultural productivity and food security, it led to a dramatic rise in the use of synthetic

BOX 2.2: Nitrogen in Waters Runs Deep

Runaway nitrogen lost to the environment not only affects surface water quality but also compromises the safety of groundwater extracted from wells. According to the Food and Agriculture Organization of the United Nations, nitrates are the most common chemical contaminant found in groundwater aquifers. This is most evident in India, where nitrate contamination in groundwater aquifers is widespread. Using available well-specific data from the Central Groundwater Board of India (CGWB), it is found that nitrate levels exceed permissible levels in more than 50 percent of the districts spanning 19 states. Not only are average concentrations high, but in areas with hard rock aquifers, nitrate contamination is found at staggering depths of more than 350 meters, showing that even deep groundwater is not safe from contamination (Biswas and Jamwal 2017). Furthermore, the presence of nitrates in groundwater enhances the mobilization of other deadly pollutants such as uranium, compounding the threat of groundwater pollution (Coyte et al. 2018).

An analysis of the impact of groundwater nitrate contamination is conducted using health data from the India Human Development Survey and the CGWB well data. Because well-specific data are sparse in time and space, groundwater contamination is aggregated to the district level. The analysis finds suggestive evidence that early-life exposure to high doses of nitrates is related to lower height-for-age scores of children aged four to eight years, after accounting for confounding factors that are correlated with groundwater contamination and health.

fertilizers such as nitrogen, phosphorus (phosphate), and potassium. The fivefold rise in the intensity of use of these fertilizers since the mid-1960s resulted in profound changes to the nitrogen cycle and exacted a toll on India's waters, with increased concentrations of nitrate and nitrite in rivers. To assess longer-term effects of nitrogen on height, various data sources were assembled, as described in box 2.3.

The results strongly suggest that nitrate exposure experienced by infants has durable, long-term impacts that stretch well into adulthood. An infant girl who is exposed to levels of nitrates above the safety threshold in the first three years of her life experiences a decrease in adult height of around 1 to 2 centimeters. Figure 2.2 shows the impact of nitrate exposure across different periods of a child's life. Short-term exposure in the years from birth to age three has a statistically negligible effect on adult height. However, cumulative exposure over the entire period has a significant and detrimental effect on height (the zero line is not crossed, and the confidence interval lies in the negative domain). This implies that developing infants are likely resilient to short episodes of nitrate exposure but that when exposure occurs over the long term, greater effects on height emerge.

Illustrating the magnitude of this impact, female adult height in India has increased by approximately 4 centimeters over the last century (NCD Risk Factor Collaboration 2016). Thus, nitrate exposure in infancy can wipe out almost half of this gain in height.

To ensure the results are not driven by confounders, and that the upstream-downstream geographic relationship of river flow credibly isolates quasi-random variation in pollution that originates upstream, the

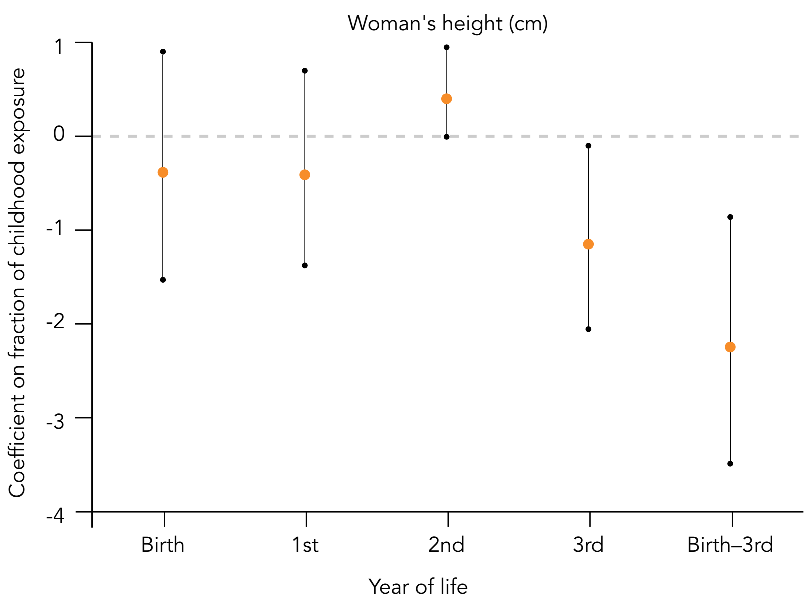
BOX 2.3: Data for India

To understand the long-term effects of nitrate pollution, a comprehensive database of water pollution measurements was assembled, the data for which were sourced from India's Central Water Commission and Central Pollution Control Board. The data set covers around 1,330 monitoring stations from 1963 to 2017. In addition, the analysis uses the most recent nationally representative Demographic and Health Survey (DHS) results to measure health outcomes. With a focus on women, DHS data are considered among the highest-quality internationally comparable data sources on health in developing countries. For the analysis, the birth-year histories of all adult women who were sampled in the DHS data are traced. These birth years range from 1966 to 1999, a period when the effect of the Green Revolution was already in force yet nitrogen fertilizers were still increasing in use. A comparison of later-life health outcomes among cohorts with more and less pollution exposure is undertaken after accounting for a rich set of controls.

analysis is subjected to various robustness checks (see the appendix and Zaveri et al., forthcoming, for details). For example, different exposure periods are tested to ensure that exposure during the critical window period for early childhood development is the dominant pathway of exposure. To ensure that the results are not being driven by spurious spatial correlations, a falsification test is also conducted. This effectively replaces the upstream pollution variable with a falsified value using pollution data from the nearest off-river region farther downstream—a location from where the pollution cannot flow (upstream) to areas where the health outcomes are measured. The results reveal that there is no significant impact of the falsified value on health, bolstering the results. Furthermore, these effects hold after accounting for exposure to other water quality indicators related to sanitation, such as fecal coliform.

These early-life exposures translate into major productivity losses. Using estimates of the economic returns to height assumed in the World Bank Human Capital Project and wage data from the Indian Human Development Survey, it is found that the nitrogen-affected adults incur a 3.4 to 9.0 percent wage penalty.

FIGURE 2.2: Impact of Nitrates on Adult Height, India



Note: This figure shows point estimates and 99 percent confidence intervals for coefficients derived from five separate regressions that estimate nitrate exposure in the year of birth (birth), year after birth (1st), two years after birth (2nd), three years after birth (3rd), and cumulatively from the year of birth up to age three (birth–3rd). The confidence interval for the last line (birth to three years) does not cross the zero-impact line and the point estimate shows the largest impact.

NITROGEN LEGACY IN VIETNAM

In Vietnam, home to one of the fastest-growing and urbanizing societies in the world, agricultural growth and intensification have played significant roles in spurring development. But in parts of the country, the environmental footprint of the agricultural sector is deepening. In intensively farmed areas, agriculture has become a major, if not the leading, contributor to water pollution. This is particularly so in the intensively farmed Mekong delta region (Cassou, Jaffee, and Ru 2018; Chea, Grenouillet, and Lek 2016).

To measure the consequences of nitrogen pollution, the analysis focuses on children aged four to twelve years surveyed in the latest Living Standards Measurement Study round of 1997–98. Because nitrate-nitrogen levels in Vietnam are relatively lower, exposure to nitrate pollution is examined at levels that are above the 75th percentile in the distribution, or roughly 2 milligrams per liter (mg/L).

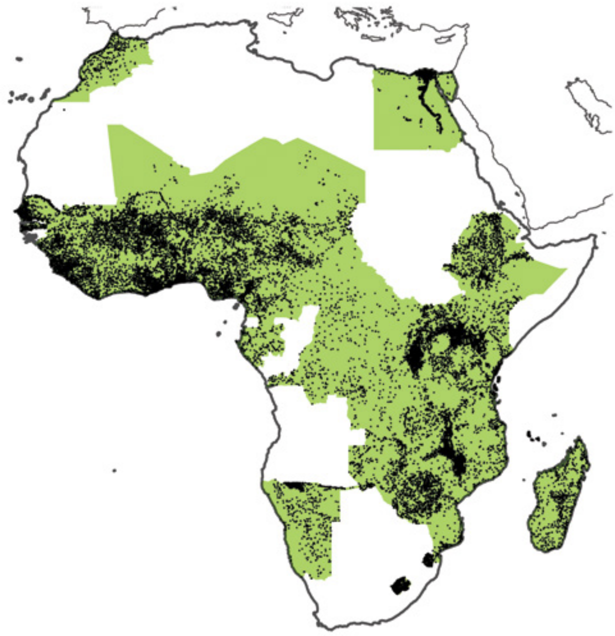
Once more, the results show that repeated exposure to nitrate pollution for the first three years of life substantially lowers height-for-age scores in childhood, with full exposure decreasing height-for-age scores by 0.7 standard deviations. These effects occur despite nitrate-nitrogen concentrations being below the recommended safety thresholds of 10 mg/L and emerge even after accounting for exposures from other contaminants.

NITROGEN LEGACY IN AFRICA

In Africa, although present-day fertilizer usage is lower than in Asia, it is growing. Other sources of nitrate exposure include expanding urban centers that lack wastewater treatment facilities and increased livestock farming. The analysis is based on the entire universe of child records up to age 5 years across 33 countries in Africa from DHS records. Map 2.2 shows the 31 countries included in the analysis from Sub-Saharan Africa, as well as the Arab Republic of Egypt and Morocco. The dots represent the approximate locations of the communities where households in the survey live. Each birth record is matched to nitrate pollution flowing from urban centers that are farther upstream. Nitrate values are predicted using a machine learning algorithm that follows the methodology explained in the appendix.

The results show that in utero exposure to nitrate pollution emanating from upstream urban agglomerations lowers the height-for-age scores and increases the likelihood of stunting for children younger than five years, even at low levels of nitrate exposure. The negative effects are most pronounced downstream from urban centers where nitrate levels are relatively higher. Stunting already remains a widespread problem in Sub-Saharan Africa, where more than 35 percent of children younger than five years are considered stunted (World Development Indicators). This suggests an urgent need for potable water treatment in urban agglomerations.

MAP 2.2: Countries Studied, Africa



Source: Demographic and Health Survey (DHS) Program.
Note: The map shows locations of enumeration areas that were surveyed as part of the DHS Program.

CAUSAL LINK BETWEEN NITRATES AND LONG-TERM HEALTH OUTCOMES

These results are perhaps the first demonstration of such widespread links between exposure to elevated nitrate levels during early-life and long-run health outcomes. Nevertheless, they are consistent with several well-established streams of biomedical literature that are indicative of such a link. First, increased dietary-nitrate intake has been associated with hypothyroidism and thyroid cancer (Aschebrook-Kilfoy et al. 2012; Ward et al. 2010, 2018). The thyroid is an important gland for regulating hormone production and metabolism regulation. Hypothyroidism in children is therefore linked to stunting of growth and a delay in the process of maturation (Wilkins 1953). Thus, the path from increased nitrate consumption from water, to diseases of the thyroid, to stunted growth and development is seemingly clear and direct. Another potential causal link between nitrates in water and reduced health and growth is through the buildup of algae and bacteria in water. As discussed in detail in chapter 4, nitrogen in waterways often causes cyanobacteria-fueled algal blooms. These bacteria can emit cyanotoxins that are toxic to humans and, if consumed, can lead to diarrhea-related illnesses.[7] As discussed earlier in this chapter, repeated bouts of diarrhea increase the probability of nutritional deficiencies in children and thus stunted child development. Exposure to such toxins can also adversely affect birth outcomes by lowering infant birthweight (Jones 2019), an important predictor of stunting later in childhood (Christian et al. 2013).

Finally, and related to the prior point, exposure to higher levels of pathogens can disrupt the gut microbiome. The first months after birth are particularly critical for establishing the composition of the gut microbiome that persists for the rest of a person's life (Robertson et al. 2019). There is evidence in the medical literature that this microbiome is difficult to permanently change later in life, although this matter is under debate. If true, then the resulting change in gut microbiome from exposure to nitrate-induced toxins like those from cyanobacteria could permanently handicap the digestive system of individuals and reduce their capacity to absorb nutrients throughout their lives. However, more research is required on how and when exposure of fetuses and young children to high nitrate levels influence microbiome function, growth, and development, especially in settings in which pathogenic infections and food insecurity are problematic.

BOON AND CURSE OF NITROGEN FERTILIZER

Across multiple geographies, this chapter has documented that an increase in nitrate pollution can lead to substantial deterioration in health and productivity. But nitrogen is also an essential input in modern agriculture, which boosts food security and can in turn provide health benefits and improve long-term economic growth (McArthur and McCord 2017). Globally, an additional kilogram per hectare of fertilizer increases yields by 4 to 5 percent. At the same time, nitrogen fertilizer runoff and the subsequent release of nitrates in the waterways can impair human health.

To get a sense of these trade-offs on a global scale, a cross-country analysis is employed following the methodology detailed in box 2.4. The analysis shows that every additional milligram per liter of nitrate that enters the water increases stunting of children younger than 5 years by 11 to 19 percent and decreases adult earnings by 1 to 2 percent.

Although these estimates are not easily translated into monetary terms, the magnitudes suggest that the marginal loss of health and later-life productivity could outweigh the marginal gain in yields associated with an additional unit of fertilizer application. In places where nitrogen use exceeds optimal levels for plant growth, this calculation tilts further in favor of reducing fertilizer use. Though these estimates are broad and imprecise, they suggest that fertilizer policies and vast fertilizer subsidies—amounting to US$11.6 billion per year in India alone (Gulati and Banerjee 2015)—require careful scrutiny.

BOX 2.4: Estimating Global Effects of Nitrate Pollution on Health

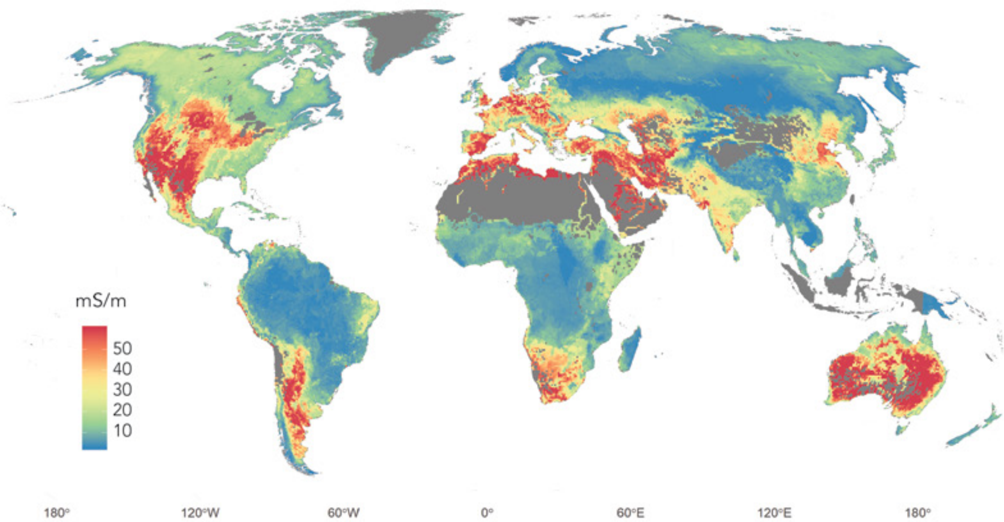
Nitrogenous fertilizer boosts yields and is essential for food security. But are the health costs associated with nitrate pollution—a result of overfertilization—low enough for the use of nitrogenous fertilizer to be socially efficient? To illustrate the economic significance of this trade-off, a global estimate of health impacts is undertaken by zooming out to all regions of the world. For the purpose of this analysis, 200 Demographic and Health Survey (DHS) records across 58 countries are collapsed into country-year observations and matched with data from other sources. Gross domestic product (GDP) and total population of children younger than five years are taken from the World Development Indicators and United Nations Population Division databases, whereas all other variables are from DHS records. The mean concentration of nitrate pollution in a country is derived from a machine learning algorithm described in the appendix. Using these data, a basic cross-country regression is estimated to measure the elasticity of stunting of children younger than five years to increases of nitrates in the water. To ensure that the result is not an artifact of trending variables, the model controls for year-fixed effects. To rule out concerns that nitrate pollution is merely a reflection of general economic development, a control for GDP is included. Similarly, to rule out concerns that the resulting impact on stunting is driven by spurious changes in certain countries or by genetic differences, the model accounts for region-fixed effects and controls for average height of mothers of measured children, along with additional time-varying controls, such as female literacy rates, and share of population with unimproved water and unimproved sanitation—factors that are likely to be correlated with stunting rates. Furthermore, using estimates of the economic returns to height assumed in the World Bank Human Capital Project, the costs to later-life productivity are approximated.

SALT POLLUTION: A PINCH TOO MUCH?

Another critical indicator of SDG 6.3.2, electrical conductivity, provides a measure of salinity.[8] Much like the scourge of nitrate pollution, salinization remains a significant problem today.

Map 2.3 illustrates the spread of the problem that is predicted using the machine learning algorithm described in the appendix. The map shows that the extent of surface water salinization is pervasive—from low-lying coastal areas in Bangladesh, to arid regions in the Middle East, to towns in Western Australia, where an area equal to one football oval an hour is said to be lost because of spreading salinity (Murphy 1999). Much of the increased salinity is a consequence of an interconnected suite of anthropogenic pressures such as irrigation, leaching of fertilizer, stormwater runoff, and urban wastewater discharge. These matters are discussed in more detail in chapter 4, which deals with the drivers of pollution.

MAP 2.3: Predicted Hotspots of Electrical Conductivity



Note: The map shows predicted values of electrical conductivity (EC) in surface water derived from a machine learning algorithm described in the appendix (available at www.worldbank.org/qualityunknown). EC serves as an indicator for salinity. There are no health-based standards for salinity in drinking water from the World Health Organization. mS/m = millisiemens per meter.

Although it is widely recognized that salinity is harmful for agriculture, there are lesser known impacts on human health. Sodium is one of five essential electrolytes that a human body needs to maintain the right balance of fluids. But too much exposure to saline water can be harmful. Physicians have long linked salt to increased risk of hypertension[9] in both adults and children (He and MacGregor 2009; He, Marrero, and MacGregor 2008). But it can also cause or aggravate a host of adverse health effects that can impact children, adults, and pregnant women. As with other pollutants, these health effects can occur because of contemporaneous exposure to salinity, as well as in utero and early childhood exposure.

The most acute impacts are seen when exposure to saline water occurs in the most vulnerable phases of the life cycle: pregnancy and infancy. Much of the evidence comes from Bangladesh, where salinity is endemic in the coastal areas and where at least one-third of the population drink saline water. A rise in drinking water salinity is linked to high levels of infant and neonatal death (Dasgupta, Huq, and Wheeler 2016; Naser et al. 2018). Recent evidence shows that around 3 percent of infant deaths in the coastal subdivisions of Bangladesh can be attributed to increased drinking water salinity and that in some divisions, such as Barisal, this rate rises to 20 percent (Naser et al. 2018).[10] Similarly, women living within 20 kilometers of the coastline are 1.3 times more likely to miscarry than those who live inland (Savage 2018). Maternal exposure to high amounts of salt during pregnancy can also lead to a higher risk of preeclampsia and gestational hypertension (Khan et al. 2014). Ultimately, it can cause irreparable harm to children through preterm birth or intrauterine growth restriction and low birthweight.

Although the impacts may be expected in a country such as Bangladesh, which suffers from extremely high levels of salinity, similar results are found in regions with lower levels of exposure in other countries. For instance, in Colombia, in utero exposure to salinity is found to increase the likelihood of fetal death. When electrical conductivity is 1 standard deviation above average, fetal deaths increase by 4.0 percent and infant deaths (aged 0 to 1 year) increase by 0.3 percent. The impact is strongest if exposure occurs in the first and second trimesters. Furthermore, for babies who are just born, in utero exposure to salinity lowers the Apgar score,[11] a summary measure for the health of newborn infants (Moster et al. 2001) and an important predictor of health, cognitive ability, and behavioral problems later in life (Almond, Chay, and Lee 2005). In Colombia, the electrical conductivity values are highest in the central Andean region and the northern coastal region bordering the Gulf of Mexico.

Salinity can also catalyze a suite of other effects by displacing and enhancing the mobilization of toxic trace elements. For example, when Flint, Michigan, switched its primary water source to the Flint River in 2014, the river's high salt load, combined with a lack of corrosion-control treatment, stripped lead from the city's aging water pipe infrastructure, which leached into the water pipes (Pieper et al. 2018; Pieper, Tang, and Edwards 2015). High levels of salt are also associated with increased concentrations of contaminants such as fluoride, boron, selenium, and arsenic (Vengosh 2003).[12] Lastly, salinization is a result not only of ions that make up common salt—sodium and chloride—but also a cocktail of salt ions such as bicarbonate, magnesium, sulfate, and potassium, which together can amplify the harmful effects of salt pollution (Kaushal et al. 2018).

KNOWN UNKNOWNS AND A SHROUD OF UNCERTAINTY

Stated simply, uncertainty is the lack of exact knowledge. Understanding how pollution manifests in humans and ecosystems is shrouded in uncertainty across three important dimensions: (a) level uncertainty (Are the prescribed safe limits actually safe?), (b) time uncertainty (Are the impacts acute or chronic?), and (c) outcome uncertainty (What are the range of impacts?; box 2.5). These multiple dimensions of uncertainty mean that the scale of the problem is still largely unknown, even for pollutants that are widely monitored and regulated. Worse, regulations guiding safety standards are often fragmented across countries and agencies, adding to uncertainty.

BOX 2.5: Many Pollutants, Many Impacts

Biological oxygen demand (BOD) is a proxy measure that captures the outcome of a host of pollutants that affect dissolved oxygen. Untreated human waste is one of the determinants of BOD (see the appendix).[a] Because of data deficiencies, few studies have been able to track consequences beyond first-order health impacts. Analyses undertaken in Brazil and Mexico indicate some second-order impacts. In Mexico, increases in BOD above the recommended threshold of 6 milligrams per liter prescribed by the National Water Commission (Comisión Nacional del Agua) are found to increase the incidence of diarrhea-related hospitalization rates by 7 to 12 percent. This suggests that the pathogens associated with increases in BOD—an umbrella proxy for water quality—can increase water-related diseases. These health impacts in turn are associated with higher health expenditure (a 22 percent increase), especially among households in the bottom tercile of the income distribution. Similarly, in Brazil,[b] exposure to a range of water quality indicators (fecal coliforms, conductivity, and derivatives of nitrogen) are found to cumulatively affect health, leading to a 14 percent rise in hospitalization rates for children in the state of São Paulo alone. Although this is perhaps not surprising, the results provide supportive evidence for a greater focus on water quality issues and the need to track numerous water quality indicators.

a. www.worldbank.org/qualityunknown.
b. The Brazilian data set directly reports the number of diarrhea and dehydration occurrences. For the Mexican data, codes A00 to A09 from the International Classification of Diseases and Related Health Problems, 10th Revision (ICD-10), are used because of their link to diarrhea-related illnesses.

In general, regulatory agencies recognize that health risks can be acute and chronic. Acute risks can cause immediate harm, whereas chronic risks can take years, if not decades, to manifest. This makes it difficult to establish safe thresholds. Recognizing that the potential health risks are often unknown or hard to predict, regulators aim to set drinking water standards at some fraction of the level of "no observed adverse health effects" (McCasland et al. 2012). The idea is to build in a margin of safety into the standard when there is more uncertainty about the health effects.

But in the case of nitrates, there may not be a safety margin for the U.S. Environmental Protection Agency's prescribed 10 mg/L safety threshold. This limit is based on the risk of methemoglobinemia (blue baby syndrome), but it does not account for other chronic health effects that could emerge at levels well below prescribed limits. As shown in this chapter, longer-term health impacts can occur at levels that are lower than the prescribed standard. Emerging evidence from epidemiological studies further bolsters the call for more stringent standards. These studies have found relationships between nitrate ingestion and cancer, thyroid disease, and adverse pregnancy outcomes, such as neural tube defects, at concentrations below regulatory limits (Temkin et al. 2019; Ward et al. 2018). Even as far back as 1977, a report by the U.S. National Academy of Sciences warned that "there is little margin of safety" in the 10 mg/L safety limit for nitrates (National Research Council 1977).[13] More research and assessments are needed to make definitive claims. Even so, the body of evidence so far suggests that the number of people impacted by nitrate-contaminated water is likely to be larger than is often presumed. For better understanding of these impacts, it will be critical to link even more water quality data to health data by individual. Global household survey programs such as the United Nations Children's Fund Multiple Indicator Cluster Surveys program have developed methods for the direct testing of water in household surveys and have mostly focused on fecal contamination, as indicated by the presence of the bacterium *Escherichia coli*. It would be useful to also embed nitrate tests in parallel with *E. coli* assays of drinking water in such surveillance programs.

As is the case with nitrates, uncertainties related to salinity loom large. As shown in this chapter, the impacts of salinity are widespread and not necessarily contained within low-elevation coastal zones where salinization is severe—health impacts are found even in Colombia, where salinity levels are lower than those reported in Bangladesh. Although regulatory agencies recommend salinity guidelines, these are based on aesthetic criteria, established for water hardness, odor, and taste. The evidence from this chapter suggests that the issue of salt will have to be taken far more seriously as salinity becomes more pervasive. As more studies emerge documenting low-level, chronic environmental exposure, a second look at what constitutes safe levels will become increasingly important. Similarly, assessments of arsenic, summarized in annex 2.1, find that impacts occur far below established safe norms.

Oftentimes, people are exposed to a combination of pollutants. Uncertainty regarding the cumulative health impacts associated with a combination of pollutants adds an additional layer of complexity to the challenge of water pollution. Across all analyses in this chapter, correlated pollutants are controlled for where possible, but only the health impacts of specific pollutants are measured. Therefore, the health risks documented in the analyses do not account for the combined health impacts of co-occurring pollutants (Stoiber et al. 2019) that may be even more harmful than the sum of the individual impacts.

In conclusion, the uncertainty regarding where safe thresholds might lie and the timing and range of impacts call for not only greater research but also wider public acknowledgement of the limitations of current understanding. In such circumstances, the provision of clear and understandable guidelines about the existing evidence and uncertainties involved would empower consumers to make choices that better align with their risk preferences. For instance, those who are highly risk averse could choose to invest more in avoiding potential impacts than those who are less risk averse.

ANNEX 2A

THE MANY UNCERTAINTIES OF ARSENIC CONTAMINATION IN DRINKING WATER

Arsenic pollution is a problem that affects millions across the world. Some 20 million Bangladeshis, about 12 percent of the population, are part of what the World Health Organization (WHO) calls "the largest poisoning of a population in history" (Smith et al. 2000). Long-term exposure to high levels is reported to cause around 1.2 million cases of hyperpigmentation, 600,000 cases of keratosis, 125,000 cases of skin cancer, and 3,000 fatalities from internal cancers every year in Bangladesh (Yu, Harvey, and Harvey 2003). But even in nations that have been highly proactive, such as Chile, adherence to guidelines has not protected people from the effects of long-term exposure to arsenic.[14]

Until the mid-1900s, northern Chile remained sparsely populated and drew drinking water from arsenic-free rivers. When the population surged following the mining boom of the 1950s, water was drawn from more sensitive sources and arsenic concentrations increased tenfold, exposing residents to levels of arsenic up to 17 times greater than the WHO recommendation of 10 micrograms per liter (μg/L) (Fraser 2012). The problem of arsenic in drinking water was solved in Antofagasta, the most populated city of northern Chile, in the 1970s through the creation of a treatment plant and increased use of desalinated water. However, 27 localities, home to more than 800,000 inhabitants (more than half the population of northern Chile),[15] were still exposed to unsafe levels of arsenic in water in the 2010s. Those violations were frequent: In and around Iquique, one of the three biggest cities of the north, arsenic levels in drinking water were greater than 10 µg/L 94 percent of the time between 2011 and 2018. In an additional 83 localities of the 392 surveyed by the Superintendence of Sanitary Services (Superintendencia de Servicios Sanitarios), the level of arsenic in water reached exactly the threshold of 10 µg/L fixed by WHO. Large parts of the volcanic north of Chile had access to arsenic-contaminated drinking water until 2017.

Besides debilitating long-term effects, acute impacts at relatively low levels are discernable. Using 11.6 million records of hospital admissions between 2011 and 2017 from the Department of Health Statistics, it is found that when arsenic in drinking water is above the WHO recommendation of 10 µg/L, hospital admissions increase by 30 percent for abdominal pain, vomiting, and dehydration, health issues that are commonly related to arsenic exposure in the medical literature.[16]

Acute effects are found at the 10 µg/L threshold. As recently as 2001, the U.S. Environmental Protection Agency (EPA) considered 50 µg/L to be the safe threshold for arsenic in the United States, and this level was associated with long-term effects. The memorandum announcing the change of threshold stated: "Although acute exposures to high doses of inorganic arsenic can cause adverse effects, such exposures do not occur from public water systems in the U.S. that are in compliance with the existing [maximum contaminant level] of 50 µg/L" (EPA 2001).

Furthermore, analysis of the rich labor microdata from the Chile National Survey on Employment shows that these health impacts translate into a decrease in worker productivity. When levels of arsenic in drinking water are above 10 µg/L in a commune, average weekly work time per worker decreases by between 30 minutes and 2 hours compared with months with levels of arsenic below 10 µg/L. Moreover, the probability of being employed during these affected months decreases by 5.6 percent. The results of a single study should not determine policy. However, they epitomize how uncertain many of these safe thresholds are and the need for more scrutiny.

These effects are substantial for levels of arsenic that are significantly below those observed in countries such as Bangladesh. For example, around 13.8 percent of wells in Bangladesh have estimated levels of arsenic greater than 50 µg/L—a level reached in only one location in Chile. Large parts of the Democratic Republic of Congo, Papua New Guinea, the Russian Federation, Vietnam, Zambia, and the Amazon basin may also be at risk of unsafe levels of arsenic in groundwater (Amini et al. 2008), potentially affecting several million people. In China alone, about 19 million people rely on groundwater that is contaminated with arsenic at levels that exceed 10 µg/L (Rodríguez-Lado et al. 2013).

NOTES

1. www.worldbank.org/qualityunknown.
2. Estimates based on 2015 figures provided in WHO/UNICEF (2017).
3. A comprehensive meta-analysis shows that on average, neighborhood open defecation corresponds to a fall of 0.46 height-for-age z-score points for children younger than five years (Gertler et al. 2015).
4. 10 mg/L as nitrate-nitrogen (NO_3-N), which is approximately equivalent to the WHO guideline of 50 mg/L as NO_3.
5. Several biomedical and epidemiological studies in the United States and other countries have documented a relationship between agrichemical exposure and birth defects, especially for children conceived during the crop-sowing months and among children of agrichemical applicators who are consistently exposed to toxins (Garry et al. 2002; Heeren, Tyler, and Mandeya 2003; Winchester et al. 2009).
6. In Senegal, studies have recorded NO_3-N levels beyond 40.0 mg/L, more than four times the safety limit for NO_3-N. Extremely high levels of NO_3 have also been reported in Gaza, where NO_3 reached concentrations of 500.0 mg/L of NO_3 in some areas (10 times the safety limit for NO_3), and more than 50 percent of public supply wells had NO_3 concentrations above 45.0 mg/L of NO_3. Other site-specific studies in India have found NO_3 in drinking water supplies to be particularly high in rural areas, where average levels are reported to be between 46.0 and 66.6 mg/L of NO_3, with maximum levels exceeding 100.0 mg/L of NO_3 in several regions.
7. Health Effects from Cyanotoxins: https://www.epa.gov/cyanohabs/health-effects-cyanotoxins.
8. Electrical conductivity is directly related to salinity, because dissolved salts contain both positively and negatively charged ions, which conduct electricity. When salinity is measured using electrical conductivity, the units are given in siemens per meter (where siemens is a standard unit for conductance). The relationship between salinity and electrical conductivity changes as water temperature changes. For a given level of salinity, electrical conductivity will rise as temperatures rise. Therefore, most reported readings are standardized to 25°C. More details on the relationship are provided in chapter 3.
9. A typical healthy adult has a blood pressure of 115 millimeters (mm) systolic and 75 mm diastolic (referred to as 115/75). Anyone with a blood pressure that is consistently higher than 140/90 has hypertension.
10. These effects are seen when salinity exceeds the threshold of 4 decisiemens per meter.
11. The Apgar score comes from a series of five tests performed 1 and 5 minutes after a child is born: appearance, pulse, grimace, activity, and respiration. Each test can receive a score on a scale of 0–2, with higher values indicating better health. A score greater than or equal to 7 is said to indicate good health.
12. Many water resources in China, east Africa, and India characterized by high fluoride content are associated with elevated salinity and widespread dental and skeletal fluorosis (Murphy 1999).
13. The report notes that "available evidence on the occurrence of methemoglobinemia in infants tends to confirm a value near 10 mg/L nitrate as nitrogen as a maximum no-observed adverse-health-effect level, but there is little margin of safety in this value" (page 424).
14. For instance, in Antofagasta, a city in northern Chile, lung and bladder cancer risks remain 40 percent higher today because of high arsenic concentrations in drinking water that occurred between 1958 and 1970 (Steinmaus et al. 2013). Long-term exposure to high concentrations of arsenic in the region are also linked to higher risk of pulmonary tuberculosis (Smith et al. 2011).
15. Population figures from the 2017 census.
16. The following International Classification of Diseases (ICD)-10 codes were selected for analysis due to their link to acute arsenic exposure: abdominal pain (R10), vomiting (R11), diarrhea (R19), dehydration (E86), vertigo (A88, H81, and T75), and hemolysis (D55–D59; Pontius, Brown, and Chen 1994).

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CHAPTER THREE

SALT OF THE EARTH

Why, if Ur was an empire's capital, if Sumer was once a vast granary, has the population dwindled to nothing, the very soil lost its virtue?

—Leonard Woolley, *Ur of the Chaldees*

KEY POINTS

- Although agriculture is often thought of as a major contributor to declining water quality, it is also a victim.
- Saline water supplies are a widespread problem across the world, significantly hampering agricultural productivity.
- Enough food is lost because of saline water each year to feed 170 million people—or a country the size of Bangladesh—every day for a year.
- Widespread use of untreated wastewater for irrigation puts the health of some 885 million urban residents in developing countries at serious risk.

Can water pollution bring down great civilizations? This idea may seem like hyperbole, but it is what many historians believe contributed to the downfall of the world's first civilization. Sumer, the civilization that gave us the wheel, plow, and written language, was also the first to pioneer irrigated agriculture. The ancient Sumerian cities of the Fertile Crescent drew water from the Tigris and Euphrates Rivers to feed the largest populations the planet had seen until that point. Over time, however, these irrigation systems led to a buildup of salt in the soil of the low-lying areas around the rivers, greatly limiting what would grow there. Although attempts were made to switch to more saline-resistant crops, the reduced productivity led to a population decline and eventually the destruction of the civilization by external and internal forces (Thompson 2004). Irrigation—the technique that allowed the world's first civilization to emerge—ultimately led to its downfall. Since then, historical references have referred to "salting the earth," the ritual of spreading salt on the fields of conquered cities (Warmington 1988). Most famously, Roman general Scipio Aemilianus Africanus is said to have plowed over the city of Carthage and sowed it with salt after defeating the city-state in the Third Punic War to ensure it could never rise again.[1]

Today, salinization remains a widespread problem, and even though the impacts of salinity are known, its risks are underrepresented. As the ancient inhabitants of the Fertile Crescent learned, agriculture is sensitive to dissolved minerals and metals in water. Just as human growth is affected by harmful substances in water, the same is true for plant growth. Whereas nutrients such as nitrogen, phosphorus, and potassium aid plant growth, certain minerals, chief among them inorganic salt, can limit plant growth and thus agricultural yields. It does so for several reasons. First, highly saline water prevents plants from absorbing water through roots and plant tissues. If salt concentrations are high enough, it can draw water out of a plant, dehydrating and eventually killing it. Salt can also starve plants of needed nutrients. When salt dissolves in water, the sodium and chloride ions separate (see box 3.1 on detecting dissolved salt in water). When concentrations are high enough, these ions can displace other mineral nutrients, such as potassium and phosphorus, leading to deficiencies. In addition, the chloride ions can interfere with photosynthesis and chlorophyll production, which are necessary for plant growth.[2] Finally, when soils become rich in sodium, soil structure can be adversely affected in a way that makes plant growth difficult.

The first half of this chapter presents new research that attempts, for the first time, to quantify the impact that saline water is having on global food production. However, salt is not the only way agriculture can be impacted by water quality. Heavy metals, bacteria, and other pathogens carried by water can also impact the quality of food. This latent threat can go unnoticed and puts hundreds of millions of people at risk of illness, both acute and long term. Accordingly, the second half of this chapter describes this challenge, including novel attempts at estimating the extent of the problem and solutions.

BOX 3.1: Measuring Dissolved Salt in Water

There are two main ways to measure salinity in water. Because most dissolved solids in water will be salt ions, one way is to calculate the concentration of total dissolved solids, or the relative weight of dissolved materials in a sample of water. This is typically done by collecting a sample of water, evaporating it, and weighing what remains. Because this is difficult to do in the field or with a monitoring station, the more common way is by measuring the water's ability to conduct electricity. Electrical conductivity (EC) is directly related to salinity, because the dissolved salts contain both positively and negatively charged ions, which conduct electricity. Simple portable meters can calculate EC of a water sample, making it the preferred method.

When salinity is measured using EC, the units are given in siemens per meter (where siemens is a standard International System of Units unit for conductance). The relationship between salinity and EC changes as water temperature changes. For a given level of salinity, EC will rise as temperature rises. Therefore, most reported EC readings are standardized to 25°C.

QUANTIFYING THE SENSITIVITY OF AGRICULTURAL PRODUCTION TO SALINITY

As described earlier, salt is one of the first documented water pollutants to have wide-ranging impacts. More than 96 percent of water on Earth exists as saltwater, making the threat to contamination of freshwater supplies near universal. It is therefore no surprise that water salinity is one of the water quality parameters tracked by Sustainable Development Goal (SDG) 6.3.2.[3] This section describes the results of an analysis that estimates the sensitivity of global agricultural production to salinity in surface water (see Russ et al., forthcoming, for technical details). To do so, three analyses are conducted. The first two use regional data to estimate the effects of saline waters in India and the Mekong River basin, because these are geographies that have a more complete database, and the third zooms out to estimate the global impact using patchier GEMStat data. Details of the methodology are given in box 3.2.

Beginning with the regional analyses, surface water quality data for India are from the Central Water Commission. Data on electrical conductivity (EC) are available from 425 stations around the country. Because of proximity, and the fact that some stations are in areas that are far from regions where agriculture is irrigated from surface waters, data from 214 stations are used. As described in box 3.2, regions are matched to upstream monitoring stations to capture the

BOX 3.2: Data Used and Methodology Employed

The impact of water salinity on agricultural productivity is assessed using regression analysis. Three similar but geographically distinct analyses are conducted: India, the Mekong River basin, and global. For each analysis, the land area is split into grid cells measuring 0.1 degree on each side, which is approximately 10 × 10 kilometers at the equator. Net primary productivity (NPP), which can be converted into kilocalories (Blanc and Strobl 2013) and can be measured from satellite imagery, is used to measure agricultural performance.

NPP is combined with a new and unique land cover data set developed by the European Space Agency's Climate Change Initiative, which provides information on 37 land cover classes globally at a 300-meter resolution.[a] This ensures that plant productivity as measured by NPP is only captured in grid cells that contain significant amounts of agriculture and avoids attributing impacts to forests or other natural habitats. In all three geographic analyses, three samples were created with varying cutoffs for the amount of land area devoted to agriculture—30, 75, and 90 percent. Results are reported as a range across all three samples.

To measure salinity of water, data from three sources are used. For India, data are from the Central Water Commission, which contains 425 stations around the country. For the Mekong River basin, data were provided by the Mekong River Commission, which includes 121 stations across four countries: Cambodia, the Lao People's Democratic Republic, Thailand, and Vietnam. For the global analysis, data from GEMStat were used, which contains 1,124 stations in 36 countries since 2000 (map 3.1).

In all analyses, monitoring station data are linked to land through the use of a digital elevation model as described in box 1.1. Grid cells are matched to the nearest monitoring station, with a distance threshold of 100 kilometers used as a cutoff. In addition, data on irrigation is used to ensure that only irrigated land is included in this study. These data include a global map on irrigation from the Food and Agriculture Organization of the United Nations[b] and data on surface irrigation by district for India, obtained from the Ministry of Agriculture and the International Crops Research Institute for the Semi-Arid Tropics.

A panel regression is estimated that attempts to isolate the impact of salinity in water on crop yields. To do so, it compares crop yields in the same grid cell across years, when levels of salinity change, while controlling for a plethora of other factors that can also impact agricultural productivity. Chief among these are weather shocks, which can impact the water balance and therefore concentration levels of pollutants. To control for weather, global gridded data on temperature and precipitation are used (Matsuura and Willmott 2012a, 2012b). Finally, a comprehensive set of controls are

box continues next page

BOX 3.2: Data Used and Methodology Employed *continued*

used, including grid cell–fixed effects, year-fixed effects, and administrative-level time trends. These are meant to control for changes in agricultural policies, development levels, input availability, technological levels, and time-invariant factors such as terrain slope, soil type, and distance to coast or water bodies.

a. The data set is available here: https://www.esa-landcover-cci.org/.
b. The surface irrigation data set is available here: http://www.fao.org/nr/water/aquastat/irrigationmap/index10.stm.

water quality of irrigated water. Furthermore, because much agriculture in India is irrigated from groundwater, only districts where at least one-third of agriculture is irrigated from surface waters are examined.[4]

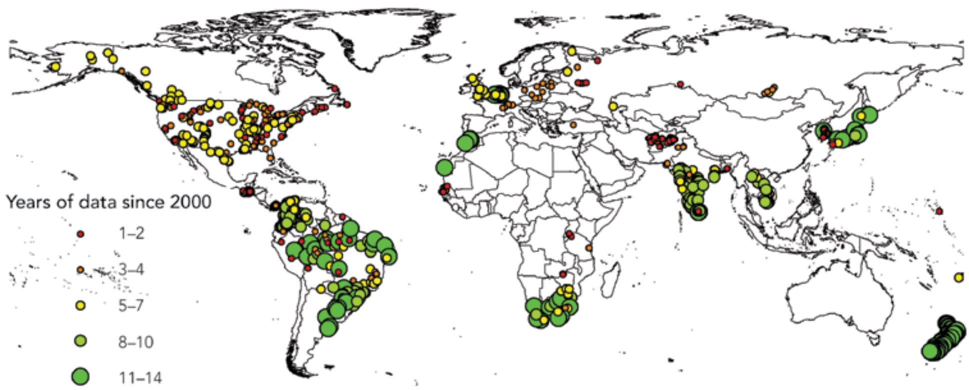
For the Mekong River basin, monitoring station data were obtained from the Mekong River Commission. Data from 121 monitoring stations covering four countries—Cambodia, Lao People's Democratic Republic, Thailand, and Vietnam—are included in this analysis. Unlike in India, groundwater irrigation is uncommon, with surface water irrigation comprising 91 percent of total irrigation in Thailand, 99 percent in Lao People's Democratic Republic and Vietnam, and 100 percent in Cambodia (Food and Agriculture Organization of the United Nations [FAO] 2016). Therefore, only regions that are equipped for irrigation are included in the analysis, and these regions are nearly all irrigated by surface water.

These analyses attempt to control for all of other factors that may affect agricultural productivity, including weather. This implies that impacts of saline water are over and above impacts caused by low river flow due to low rainfall—which is highly correlated with salt concentrations. A threshold of 100 millisiemens per meter (mS/m) was used to test for impacts. This threshold is around where the Mekong River Commission and other sources estimate that one should start seeing impacts on irrigated crops (Kongmeng and Larsen 2014; Tanji and Kielen 2002).

In India, it is found that when EC exceeds 100 mS/m, yields decline by 5.5 to 6.6 percent. Similar levels of sensitivity to salinity in irrigated water are found in the Mekong River basin. When EC exceeds 100 mS/m, yields decline by 5.8 to 8.2 percent. These results are not sensitive to small changes in the threshold. This threshold is exceeded by approximately 5 percent of observations in both India and the Mekong River basin.

The final analysis zooms out to all regions of the world where GEMStat data exist. These stations are shown in map 3.1, where the markers indicate the location of stations and the number of years of data on EC since 2000. Although it is unfortunate that there are large data gaps in Sub-Saharan

MAP 3.1: Location of GEMStat Water Quality Monitoring Stations with Data on Electrical Conductivity



Source: GEMStat database.

Africa, Central Asia, and China, stations exist in 36 countries, and the diversity of station locations is sufficient to obtain a global estimate of the sensitivity of agriculture to saline water.

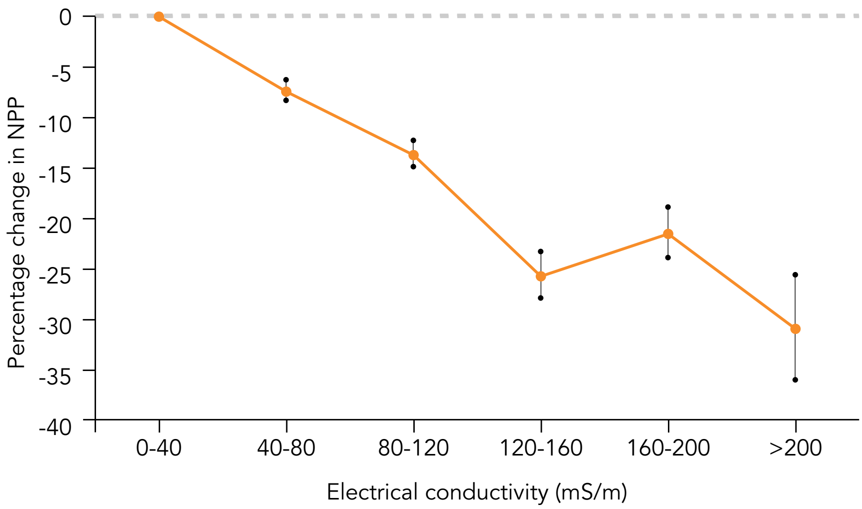
Globally, it is found that when EC exceeds 100 mS/m, yields decline by 11.0 to 13.5 percent. Here, however, there are sufficient data to estimate how the sensitivity of agricultural yields to salinity varies with the levels of salinity. Figure 3.1 shows that at even relatively low levels of EC, 40 to 80 mS/m, yields begin to decline. As EC increases, so do the impacts at a nearly linear rate, reaching losses exceeding 25 percent.

IMPLICATIONS FOR FOOD SECURITY

Water quality–induced reductions in yields have major implications for global and local food security, with the world losing a sizable portion of its food production every year to saline waters. By using the global data set on EC produced by machine learning techniques for this report (described in the appendix),[5] and because net primary productivity (NPP), our measure of yields, can be easily converted into average calories, we can fairly precisely identify the hotspots of food calorie loss. Between 2001 and 2013, an estimated 124 trillion kilocalories worth of agricultural production was lost each year because of saline water. In total, these calories represent enough food to feed more than 170 million people every day, sufficient to feed a country the size of Bangladesh for an entire year.[6]

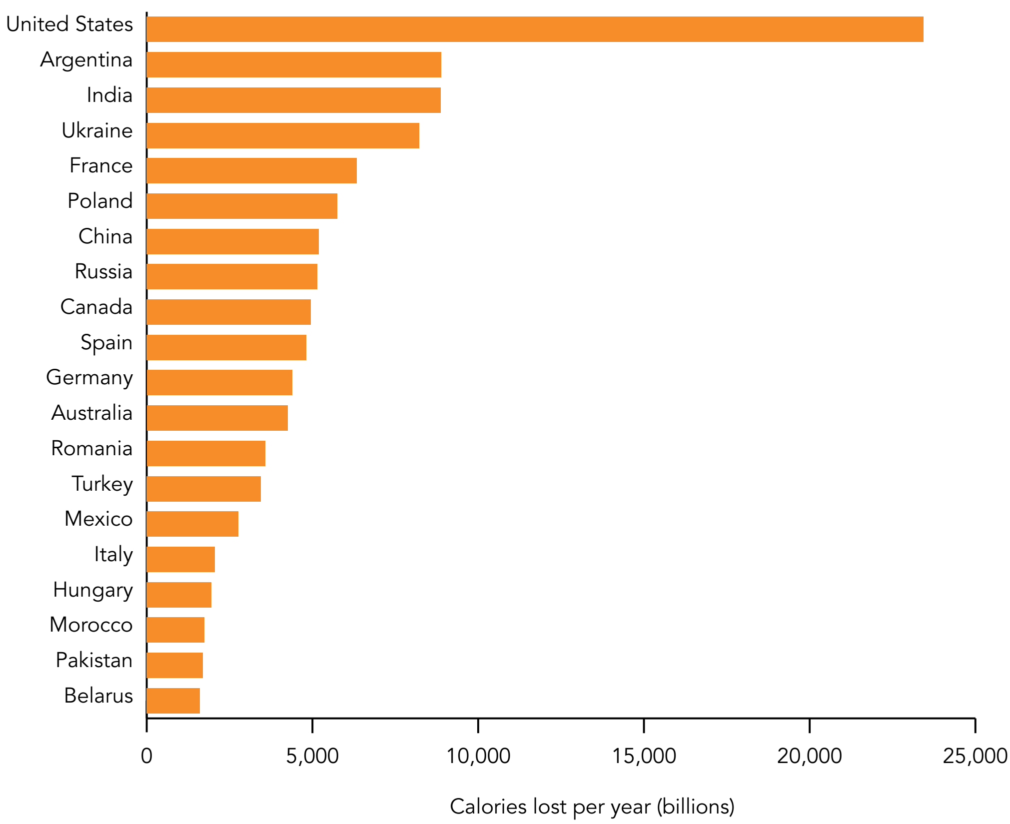
Figure 3.2 aggregates losses by country and shows that the impact is generally not correlated with development level. With the exception of Sub-Saharan Africa, where most food production is rainfed, all continents have large hotspots. Wet regions, such as the Amazon basin, Southeast Asia, and the southeastern United States also avoid losses from salinity, despite being important agricultural zones.

FIGURE 3.1: Impact of Salinity in Surface Water on Agricultural Productivity



Note: mS/m = millisiemens per meter; NPP = net primary productivity.

FIGURE 3.2: Mean Losses in Agricultural Production because of Saline Water, by Country, 2001–13



The World Bank report *Uncharted Waters* (Damania et al. 2017) performed a similar analysis but examined the global impacts of rainfall variability on agricultural productivity. It found that variability was responsible for an annual loss of 59.2 trillion kilocalories. Although attention is given to how climate change–induced rainfall variability will impact global food production, the analysis here shows that losses due to saline water are more than twice as high each year.

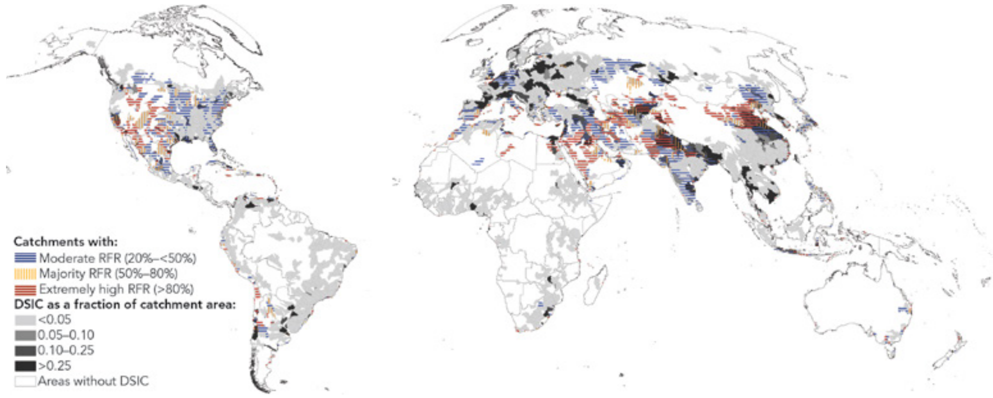
TOXIC WATER, TOXIC CROPS

The use of wastewater for irrigation is common in developing countries. In some ways, wastewater irrigation offers a triple win: it reduces the amount of water that needs to be extracted from dwindling resources; it offers a solution to discharging urban wastewater, often without treatment; and some dissolved nutrients can act as a fertilizer. Urban wastewater can contain many primary macronutrients such as nitrogen, potassium, phosphorus, and organic carbon and secondary macronutrients such as magnesium and sulfur. It is therefore no surprise that wastewater irrigation has been shown to increase agricultural yields (Singh, Deshbhratar, and Ramteke 2012).

The potential benefits of wastewater irrigation are perceived to be high. In 2010, farmers in the Mezquital Valley of Mexico protested the construction of a wastewater treatment plant, fearing that removing the harmful contaminants of the water would also remove the nutrients that many believe make the region so productive.[7] The yield benefits are so great that farmers in Pakistan are willing to pay up to 200 percent more for wastewater than they are for regular water irrigation (Ensink et al. 2002). Wastewater also has the benefit of being available year-round, including during the dry season, whereas regular water irrigation is often restricted to certain parts of the year in arid regions. The benefits of wastewater irrigation can extend past the farmers—weekly market prices for cauliflower and potatoes in Pakistan were found to fall 59 and 44 percent, respectively, when local wastewater-produced varieties entered the market, merely because of the change in the ratio of supply to demand (Ensink et al. 2004).

Nevertheless, if not carefully managed, wastewater irrigation can harm crop quality and cause health concerns and environmental damage. Urban wastewater is often high in concentrations of heavy metals, particularly in cities where heavy industry is present. When fields are repeatedly irrigated with this water, concentrations of heavy metals build up in the soil. This can be harmful both to crop production—reducing the yield benefits of wastewater irrigation over time—and to humans and animals who consume the metal-rich plants (Meng et al. 2016). Studies in China (Khan et al. 2008), India (Sharma, Agrawal, and Marshall 2006), Pakistan (Mahmood and Malik 2014), and Saudi Arabia (Balkhair and Ashraf 2016), among many other places, show that vegetable crops grown using wastewater often have significantly higher

MAP 3.2: Catchment Areas with High Wastewater Return Flow Ratios



Source: Thebo et al. 2017.
Note: Colors show regions with moderate (blue), majority (yellow), and extremely high (red) wastewater return flow ratios (RFRs). Gray areas indicate the share of downstream-irrigated croplands (DSICs) as a fraction of catchment area; darker regions have higher ratios.

levels of heavy metal concentration, exceeding World Health Organization (WHO) thresholds. Thus, consuming food grown from untreated wastewater irrigation may lead to slow poisoning over time. A recent study found that globally, 65 percent of all irrigated croplands within 40 kilometers downstream of urban areas rely heavily on wastewater flows, potentially exposing some 885 million urban residents to serious health risks (map 3.2).

Untreated wastewater can also carry bacteria, viruses, and other pathogens that can infect consumers and cause acute health impacts. In Pakistan, for instance, untreated wastewater irrigation was linked to *Giardia duodenalis* infection from a parasite, which can cause nausea and diarrhea (Ensink, van der Hoek, and Amerasinghe 2006). Households that farmed with wastewater had significantly higher risks of infection than those that did not, and nonfarming laborers employed near areas that farmed with wastewater were at risk, likely through food transmission. In the Republic of Korea, it was found that irrigating rice with wastewater increased the likelihood of *Escherichia coli* infection, especially among children. The infection was transmitted not necessarily from consumption of the rice but simply from the increased environmental risks that the water poses during cultivation. These risks subsided one or two days after fields were flooded and could be greatly reduced through ultraviolet light disinfection systems (An et al. 2007).

Irrigating with wastewater also has the potential to permanently contaminate groundwater supplies. When wastewater enters the soil, it inevitably flows downward. Depending on soil type, some of these pollutants can be filtered out. However, with repeated exposure, soils will eventually reach capacity for storing these pollutants. Once groundwater supplies become exposed, particularly in the case of nutrients and heavy metals, treatment can become infeasible (Maheshwari, Singh, and Thoradeniya 2016).

THE WAY FORWARD

Addressing the water quality needs for agriculture is a tremendous challenge. With agriculture responsible for 70 percent of freshwater abstractions globally, and the need for an additional 20 percent increase in water withdrawals by 2050 to feed a population of 9 billion, the problems of water scarcity often overshadow those of water quality. Nevertheless, the results in this chapter demonstrate that yield losses due to saline water may exceed those due to rainfall variability by a ratio of more than 2 to 1. One of the common methods for adapting to dwindling water supplies, wastewater irrigation, is causing significant public health concerns.

Although water treatment, reverse osmosis, and other forms of water purification may suffice as solutions to poor water quality for drinking water or water for industry, the economics do not work when it comes to desalinizing water for agriculture. Energy costs of desalination are simply too high to economically justify its use for nearly all forms of agriculture, where value per drop of water is low (box 3.3 discusses some challenges related to water reuse and desalination). Therefore, the focus must be on prevention of, or adaptation to, brackish or contaminated waters.

Preventing irrigated waters from becoming too saline is a matter of maintaining a steady salt balance, particularly in the root zone of the soil where crops are particularly sensitive. Salt is a naturally occurring mineral, and regardless of the source of water, low-level concentrations of dissolved salts are inevitable. This only becomes a problem when these salts are allowed to accumulate over time. Maintaining a proper salt balance therefore requires that the same amount of salt that flows into a field also flows out. Well-designed irrigation drainage systems can accomplish this while preventing waterlogging, which can also be harmful to crop productivity. Still, drainage systems must be carefully designed to ensure that they do not remove too much salt from soil layers. If draining systems do not specifically target the root layer of the soil, they may end up removing more salt from the soil than was applied by irrigation. This will cause an increase in the salt load of the water leaving the field and affect downstream water users (Christen, Ayars, and Hornbuckle 2001). However, removing more salts than have been applied by irrigation is an important and common strategy for land reclamation. Calibrating irrigation and draining solutions must therefore be carefully done to ensure the strategy is appropriate and efficient and does not simply transfer the problem from upstream users to downstream users.

Dealing with overextraction is important for reducing the occurrence of salinity in water, as well as reducing the need for wastewater irrigation. Overextraction can exacerbate water salinity through reduced dilution of downstream water. Salt, at low levels of concentration, can be benign—it is only once those concentration levels become too high that productivity declines. Removing less water out of the system is therefore the easiest way to prevent concentrations from becoming too high. When overextraction

BOX 3.3: Water Reuse and the Circular Economy

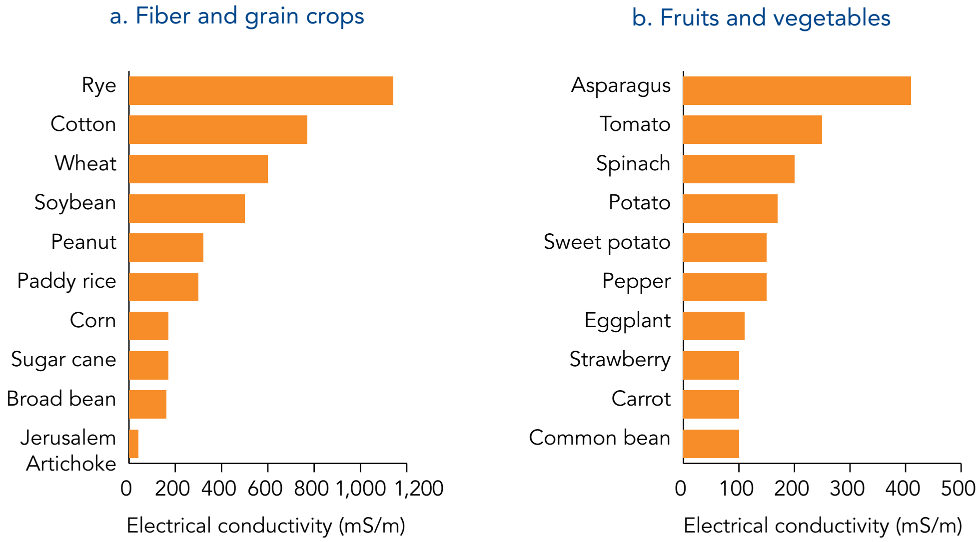
Much has been said recently about the potential benefits of attaining the circular economy. The circular economy is the idea of reusing and recycling waste back into the economy to reduce pressures on additional resource extraction and environmental degradation. Pressures from growing populations, rising incomes, and climate change make shifting toward a more circular economic model necessary if economic growth and welfare improvements are to continue. Given the tremendous needs for water for agriculture, and that so much agriculture occurs in periurban areas where wastewater is plentiful, the use of wastewater for irrigation becomes a critical component of closing the loop on water use. Nevertheless, as this section has detailed, the reuse of wastewater for irrigation is not a panacea, and it must be done with precaution to prevent trading food insecurity for disease outbreaks.

Decentralized water reuse for personal consumption is also becoming increasingly common. Where governments are unable to provide clean water, citizens and companies are taking action by purchasing small reverse osmosis machines to purify untreated water. Although these machines, which are becoming particularly popular in India, are successfully providing clean water to people who otherwise would not have access, they are not without large costs. Reverse osmosis works by using high pressure to force water through small membranes, which do not allow impurities to pass through. This is energy intensive, which is a large concern in parts of India, where power supply often cannot keep up with power demand. When used at industrial scales, reverse osmosis generates wastewater that is highly concentrated in pollutants. Perhaps most concerning, there is an absence of proper methods for disposing of the contaminated wastewater. Many households dispose of it back into the aquifer, or onto nearby soils, further contaminating water supplies and exacerbating the problem (Pérez-González et al. 2012). These problems are not insurmountable, but they call into question the viability and sustainability of decentralized water reuse.

reduces flow in rivers, it can also allow tidal highs to reach farther inland. This can allow saline water to intrude into river deltas or coastal aquifers. Naturally, low-lying coastal regions are most at risk of seawater intrusion. This is a major concern in the Mekong River delta, where seasonal salinity stress greatly impacts rice production (Kotera et al. 2008).

Adaptation through crop choice decisions becomes necessary when reducing salinity in water is too difficult or costly. Crops have different tolerance levels for saline water, with some crops experiencing large yield declines at relatively low levels of EC and others tolerant of EC levels in excess of 1,000 mS/m. Although actual tolerance levels vary based on climate, soil conditions, and cultural practices, crops can be generally categorized and

FIGURE 3.3: Salt Tolerance Levels of Selected Crops



Source: Tanji and Kielen 2002.
Note: mS/m = millisiemens per meter.

ranked based on their tolerance. Figure 3.3 gives the average maximum EC tolerance level of 20 common selected crops, with panel a showing fiber and grain crops and panel b showing fruits and vegetables. These crops are demonstrative of the range of tolerance levels and the potential to shift production to more resistant crops when saline levels become too high.

Finally, when it comes to using wastewater for irrigation, there is an urgent need for better enforcing wastewater effluent quality when it is reused in irrigation. The U.S. Environmental Protection Agency, WHO, and the European Commission all have minimum water quality requirements and guidelines for wastewater irrigation. If such guidelines are properly regulated and enforced, then irrigation with treated wastewater can be practiced safely. Unfortunately, in many developing countries, there is little capacity for, funding of, or political interest in enforcing these guidelines. Contaminated food is often indistinguishable from noncontaminated food, which puts consumers at risk and likely causes high economic costs in terms of medical expenditure and losses in labor productivity.

NOTES

1. Although this particular assertion is likely a modern invention, many other examples exist.
2. https://web.extension.illinois.edu/state/newsdetail.cfm?NewsID=5427.
3. The particular parameter that measures salinity is EC. pH, another indicator tracked by SDG 6.3.2, is also highly correlated with salinity.
4. Unfortunately, data on groundwater quality is not nearly as comprehensive or as widely available; thus, impacts are not measured in this report.
5. www.worldbank.org/qualityunknown.
6. This is based on 2,000 kilocalories per day per person, or 730,000 kilocalories per person per year.
7. https://www.nytimes.com/2010/05/05/world/americas/05mexico.html.

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CHAPTER FOUR

WATER QUALITY AND ITS DETERMINANTS

The sedge is wither'd from the lake, And no birds sing.

—John Keats, as quoted in *Silent Spring* by Rachel Carson

KEY POINTS

- Nutrient pollution is responsible for significant environmental degradation, including hypoxic events and cyanobacterial blooms, which harm aquatic life and humans alike.
- A new water quality data set generated by remote sensing shows that cyanobacteria-related algal bloom events occur more often than was previously known, nearly twice per year in 421 of the world's largest lakes.
- Changes in land use are a key factor in declines in environmental water quality. Recognizing that continued changes in land use for urban areas and agriculture are inevitable, policies should seek to strategically plan the locations of these land use changes to protect water resources.
- Rainfall variability and hotter temperatures also significantly reduce water quality, implying climate change is a risk factor not just for water quantity but also for water quality.

GASPING FOR AIR

In 2011, an environmental disaster occurred on Lake Erie. Phosphorus loads and other nutrients from nearby farms had been increasing in the preceding years. This increase in nutrients, combined with warmer than normal temperatures and increased levels of runoff in the region, caused an unprecedented and highly conspicuous bloom of blue-green algae. The responsibility for this bloom lay with *Microcystis*, a genus of cyanobacteria that thrives in environments rich in nitrogen and phosphorus, particularly when it is warmer. Conspicuous to the eyes, cyanobacteria can be deadly—they can emit neurotoxins and hepatotoxins such as microcystin and cyanopeptolin, which are toxic to humans, animals, and other aquatic life. They are also difficult to treat using conventional potable water treatment methods (Hitzfeld, Höger, and Dietrich 2000), making them particularly dangerous. Large algal blooms can also devastate ecosystems, often resulting in hypoxia, where much of the dissolved oxygen is depleted by the algae, leaving little for other species (box 4.1). There is also evidence that plant uptake of these toxins can occur in irrigation water, leading to contamination of food (Abe et al. 1996; Codd, Metcalf, and Beattie 1999).

Unfortunately, the 2011 bloom on Lake Erie was not a one-off event and was repeated just three years later. These algal blooms on the lake caused considerable alarm and even panic nationally and globally. Lake Erie is the primary source of water for more than 12 million inhabitants on either side of the border between Canada and the United States, and during the summer of 2014, 400,000 people saw their access to safe water threatened. The bloom also caused a multimillion-dollar loss for the tourism sector in the heart of the summer (Bingham, Sinha, and Lupi 2015). And during the summer of 2018, the water turned deep green for a third time.[1] To many, these repeated events are a frightening sign of what a future of increasing nutrient runoff, along with climate change–related rainfall variability and hotter temperatures, could bring.

Unbeknownst to most, these events are already far more common than is realized, even by a well-informed water quality specialist. Although Lake Erie's blooms gain considerable traction in the media—a Google News search for the terms "Lake Erie," "2014," and "algal blooms" generates more than 2,500 articles—similar events in other lakes occur frequently with little or no fanfare. The frequency of these events can be demonstrated for the first time using a new data set on water quality in global lakes developed for this report (see the appendix).[2] The data set uses satellite imagery and remote sensing, scanning for visible changes in water bodies and allowing the detection of certain water quality parameters, including cyanobacterial and algal blooms.

BOX 4.1: Nutrients, Algal Blooms, and Hypoxia

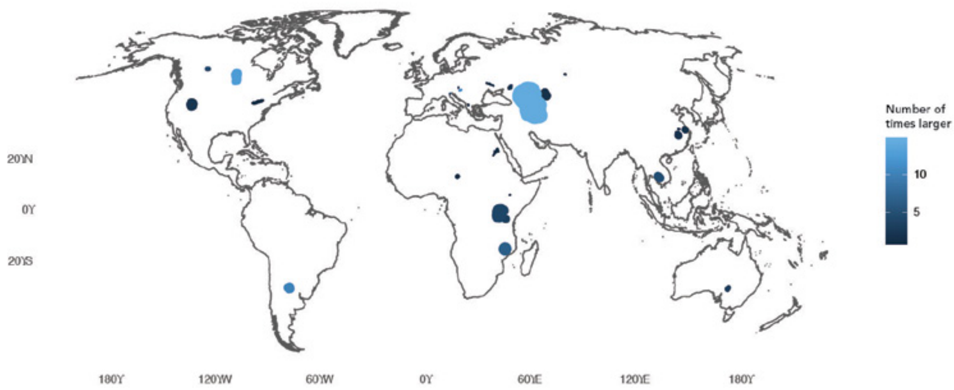
Algal blooms represent the collapse of the fragile balance of a freshwater ecosystem. A parsimony of available nutrients is a notable characteristic of most natural systems. Available nitrogen and phosphorus are vanishingly scarce in most pristine waters. This is because natural systems use nitrogen and phosphorus and recycle them. Thus, there is a strong link between nitrogen availability and aquatic plant life (James et al. 2005).

Disturbing the nutrient balance of an ecosystem favors some species to the detriment of others, upsetting the fragile ecosystem, disrupting the food chain, and in the extreme, leading to system collapse. Nutrients favor the growth of microorganisms in water, particularly the growth of chlorophyll, a photosynthetic pigment that enables green plants to undertake photosynthesis. Its presence in surface water indicates an abundance of green vegetation, mainly phytoplankton or algae. Rich waters are not necessarily bad, and chlorophyll is a natural part of a well-functioning freshwater ecosystem. However, in excess, chlorophyll can result in the development of algal blooms. These blooms consume oxygen and block the sunlight, making it harder for aquatic life to survive.

Hypoxia, a condition that arises when water bodies lack sufficient oxygen, has emerged as a growing problem throughout the water bodies of the world. Hypoxia occurs when concentrations of oxygen fall below 2–3 milligrams of oxygen per liter of water. The complete absence of oxygen leads to anoxia, creating dead zones in which few lifeforms can survive. Dead zones tend to occur at the mouths and deltas of rivers, where nutrients enter the marine system. The impacts can be long lived—ocean floors can take more than 1,000 years to recover from low-oxygen events (Moffitt et al. 2015). These events are expected to become more widespread as farming and ranching practices continue to expand and as global ocean temperatures rise because of climate change, fueling larger algal bloom events.

Between June 2002 and April 2012, more than 8,200 occurrences of floating cyanobacteria-fueled algal blooms (from the type of algae,[3] toxic to humans, plants, and animals, that bloomed on Lake Erie) were detected in lakes in the database, accounting for 21 percent of all available observations. These events were not limited to a few lakes but instead impacted 329 of the 421 lakes. Naturally, most events were small, averaging only a few hectares. Yet 222 events of recorded floating algal blooms fueled by cyanobacteria were strictly larger than the summer 2011 Lake Erie event. These events occurred in

MAP 4.1: Global Algal Blooms Larger Than Lake Erie's 2011 Event



Source: Calculations based on data from the remote-sensing water quality database described in the appendix (available at www.worldbank.org/qualityunknown).
Note: Map shows location and incidence of algal blooms that had a larger surface area on lakes than the 2011 bloom on Lake Erie.

27 lakes of the database (map 4.1). Put differently, the world experienced on average two such episodes of massive cyanobacteria-related algal bloom every month over a 10-year period.

Among these events, a few are widely known, such as the frequent blooms that occur on the Caspian Sea or Canada's Lake Winnipeg (which over 10 years recorded 52 and 13 events, respectively, larger than the Lake Erie event). Other events received little or no public news coverage, including blooms on Lake Chilwa in Malawi (29 events larger than the Lake Erie event); Lake Victoria in Central Africa, particularly its Kenyan and Ugandan parts (19 events larger than the Lake Erie event); or Lakes Chiliqua in Argentina and Tonle Sap in Cambodia (14 events each larger than the Lake Erie event). Many of these lakes are economically and ecologically critical. Lakes Chilwa and Victoria both support dynamic and biodiversity-rich fisheries that are threatened by algal blooms and other intrusive floating vegetation boosted by excess nutrients (box 4.2). The frequency of these events, coupled with the limited attention they receive, is emblematic of the water quality problem.

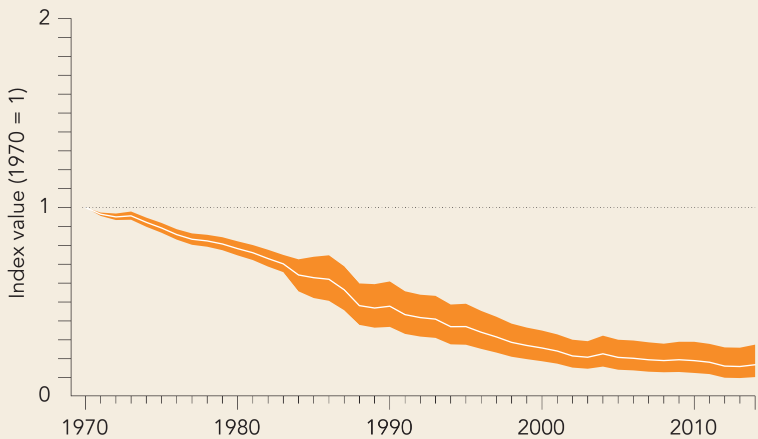
GLOBAL ASSESSMENT OF THE DRIVERS OF ENVIRONMENTAL WATER QUALITY

Increases in nutrients and decreases in runoff receive much of the blame for the weakening of freshwater ecosystems. When the word "nutrient" is mentioned, the obvious villain is the rise of fertilizers. The story is likely to

BOX 4.2: Water Quality and Fisheries

The decline in freshwater species populations is dramatic. According to *Living Planet Report 2018* (WWF 2018), freshwater populations dropped by 81 percent globally between 1970 and 2014, with more declines predicted in the years to come (figure B4.2.1). This compares to declines of 40 percent for terrestrial species and 35 percent for marine species. The International Union for Conservation of Nature (IUCN) suggests that freshwater fishes may be the most threatened group of vertebrates (Reid, MacBeath, and Csatádi 2013).

FIGURE B4.2.1: Decline in Freshwater Fish Populations, 1970–2014



Source: WWF 2018.

It is hard to determine the precise contribution of water quality to fisheries decline, but it is clear that pollution is one of the leading causes. According to one study, pollution is a threat to about 40 percent of freshwater species identified as threatened by IUCN (Arthington et al. 2016). By altering biomass, nutrient pollution impacts the distribution of species, favoring some at the cost of others. This occurs because of indirect effects such as reducing oxygen availability, increasing sedimentation on spawning grounds, and altering competitive balances, as well as direct effects. In addition, toxic discharges have directly resulted in significant fish kills (Kangur et al. 2013). At least 8 of the 13 globally extinct species of European freshwater fishes were victims of water pollution and lake eutrophication (Freyhof and Brooks 2011).

There is also growing awareness of the threat posed by emerging pollutants. Pharmaceutical products such as antidepressants and birth control pills that end up in freshwaters have caused significant damage to fish, such as sex mutation in female and male gametogenesis, caused by the disruption of complex neuroendocrine, endocrine, and paracrine regulators.

be more complex. It is not only a question of intensification of agricultural production but also of extensification and loss of natural habitats. It is also a story of rising urbanization, lack of infrastructure, and climatic events. A considerable body of literature has attempted to explain how human and environmental changes impact freshwater quality. Most of this work occurs in individual case studies, usually for a single river or lake basin, using what are sometimes startlingly different techniques.

Here, three global analyses are conducted to assess the determinants of water quality around the world. First, determinants of events in global lakes that lead to the types of algal blooms and hypoxia described earlier are examined. This is done using a novel water quality index that focuses on environmental parameters. The remaining two analyses focus on determinants of water quality in rivers, first looking at determinants of nitrogen and then at determinants of salts.

DETERMINANTS OF WATER QUALITY IN GLOBAL LAKES

The lakes database developed for this report offers a rare opportunity to examine the relative magnitudes of the key drivers of water quality in a globally consistent manner. Remote sensing—though limiting in the parameters that can be detected—allows for consistent estimates of many parameters that cause algal blooms and hypoxia. These include chlorophyll, cyanobacteria (floating and immersed), total suspended matter, and turbidity. Monthly data for 255 freshwater lakes in developing countries were used for years between 2001 and 2011.[4] Lakes were chosen based on size, with the largest lakes selected to improve data quality. Chosen lakes are thus somewhat randomly distributed around the world but are overrepresented in three countries—Argentina, India, and Mexico—where they were oversampled.

The parameters listed earlier are all part of the same natural process and significantly overlap. Thus, rather than analyzing them separately, an environmental water quality index (EWQI) was created. Many water quality indices exist—many river basin organizations or governments that collect water quality data generate their own index. An index can give an indication of the overall purity of water without confusing the user with multiple indicators and thresholds. Similar to the ultraviolet index for air quality, it can help the user determine quickly whether water is safe to drink, swim in, or consume fish from. However, it is not always clear how to combine several parameters into a single indicator, so indices are often created using subjective, equal, or somewhat arbitrary weights. Here, a statistical method called constrained principal component analysis is used, which bases the index on relationships between variables themselves. It does so in a way that minimizes the information that is lost as one moves from several parameters to a single index. Details of this index are given in box 4.3.

BOX 4.3: Generating an Environmental Water Quality Index

The world of water quality is complex. Scores of different parameters are tracked by different agencies. The GEMStat database alone tracks more than 220 parameters. Some of these parameters measure similar pollutants but in different ways. For instance, lead can be measured in terms of total dissolved, total suspended, or both. Nitrogen can be measured in the form of total nitrogen or in any of its oxidized forms—nitrite, nitrate, or ammonium nitrate. Sometimes the measure matters—nitrate-nitrogen is considered dangerous when above 10 milligrams per liter (mg/L) in concentration (though this report finds it dangerous even below this limit), whereas the U.S. Environmental Protection Agency safety level for nitrite-nitrogen is 1 mg/L. These thresholds also frequently vary from one regulator to the next or over time.

For the water quality index generated for this report, a novel approach was used—constrained principal component analysis (CPCA). CPCA is an augmented version of a well-known statistical technique called principal component analysis (PCA), a method that allows multiple criteria to be reduced into a single dimension or composite index while still preserving as much as possible of the originally input information. Importantly, PCA uses the data to determine the best way to weight different indicators, according to how they correlate with one another. CPCA follows the same information reduction approach but goes a step further by allowing the use of additional constraints to the criteria, so the resulting weights can explicitly consider domain expertise or policy preferences.

Of the variables available in the remote-sensing data, chlorophyll is the most relevant from an environmental standpoint. The environmental water quality index (EWQI) was therefore constrained so that the weight given to this variable was no smaller than the weight assigned to any other variable. The CPCA approach resulted in the weights shown in table B4.3.1 for the five available parameters.

TABLE B4.3.1: Environmental Water Quality Index Weights

EWQI indicator	Percentage indicator weight
Floating cyanobacteria[a]	11.37
Total suspended matter[b]	24.12
Turbidity[c]	22.62
Chlorophyll[d]	24.12
Immersed cyanobacteria[a]	17.76

a. Cyanobacteria (floating and immersed) are photosynthetic bacteria that share some properties with algae in that they possess chlorophyll and release oxygen during photosynthesis. The decomposition of cyanobacteria consumes dissolved oxygen contained in the water and thus oxygen concentrations decline, leading to hypoxic conditions (Brooks et al. 2016).
b. Total suspended matter in freshwater systems includes chlorophyll, organic influents, and sediment (Cai et al. 2012). High levels of total suspended matter can alter the turbidity characteristics of water (Mallin, Johnson, and Ensign 2009).
c. Turbidity is a measure of cloudiness of water. In scientific terms, turbidity describes the amount of light scattered or blocked by suspended particles. High levels of turbidity are often caused by sediment and organic matter, as well as algae, cyanobacteria, and other phytoplankton.
d. Chlorophyll is a photosynthetic pigment that enables green plants to undertake photosynthesis. Its presence in surface water indicates an abundance of green vegetation, mainly phytoplankton or algae.

The analysis here focuses on how anthropogenic factors, including land use change, population growth, and agriculture, and weather impact environmental water quality. For anthropogenic factors, a further distinction is made between extensification of human activity and intensification. Both urban areas and agricultural land can expand outward. When they do, this extensification often encroaches on natural habitats, removing trees and shrubs that protect against soil erosion and, in the case of urbanization, converting soft, porous land into hard surfaces that do not absorb water as efficiently. Alternatively (but also often in tandem), agricultural production and urban areas can intensify by becoming denser. Population density increases as cities get larger, and yields increase as agriculture becomes more productive. The spread of these activities should have a different effect on environmental water quality than the intensification of them. The distinction between the two has important implications for how cities and agriculture could be planned more sustainably when it comes to water resources. The first half of box 4.4 describes the methodology in greater detail.

It is found that extensification of human activity—including land use change for both cropland and urbanization—is likely the more important factor in reducing environmental water quality, with changes in the agricultural sector playing a more deleterious role. Quantitatively, a 10 percent increase in cropland leads to a 45 percent degradation in the EWQI, while a similar increase in urban area leads to a 1.4 percent fall in water quality. Intensification of these same activities—measured as increases in population density and agricultural yields—has a more muted impact on the EWQI.

There are several explanations as to why extensification of human activity is found to be the larger contributor to declining water quality. When lands are cleared for agricultural use, the soil loses an important source of support. Roots of trees and shrubs hold the soil together. When they are removed, soils are more easily blown or washed downslope into nearby waterways. In addition, when this land is converted into agricultural lands, the nitrogen and other nutrients that are applied to the fields wash away with the soils (Browder et al. 2019). Furthermore, the plants that comprise forests consume nitrogen and other nutrients that would otherwise be washed into waterways. By deforesting lands to expand urban areas, these important sinks for the unused fertilizers that run off farms are lost. Forested areas and wetlands are significantly more efficient at removing nutrients from water runoff than are cropped areas (Peterjohn and Correll 1984). These are average outcomes, and there is no doubt that there are a growing number of cases in which highly intensive forms of agriculture, such as intensive animal husbandry, is vastly more damaging than the typical form of extensification captured in regressions.

These results are the first of their kind and need confirmation from additional studies. However, if robust, they give important insight into sustainable planning decisions for clean water resources. The results demonstrate that spatial planning of land use may be critical for protecting water bodies. This is expanded upon in the final section of the chapter.

BOX 4.4: Estimating the Determinants of Water Quality

Determinants of Environmental Water Quality in Global Lakes

A regression approach was used to estimate the impacts of extensification and intensification of human activity on changes in the environmental water quality index (EWQI). The EWQI is measured at the annual level, and each lake has nine years of data. For each lake, the upslope area—or the land area from which runoff flows into the lake—was calculated. The regression then tests the sensitivity of the EWQI to changes occurring in the upslope area in the same year.

Land cover from the European Space Agency is used to obtain the extensification variables—cropland and urban area—in each upslope area. For agricultural intensification, net primary productivity is used to measure yields, and for urban intensification, population density is used. Finally, precipitation and temperature are obtained from Matsuura and Willmott (2012a, 2012b). These variables are described in more detail in box 3.2. In addition to these variables, the regression controls for year-fixed effects to account for global climate or economic patterns, lake-fixed effects to account for time invariant differences between lakes and upslope areas, and country time trends to account for varying economic and demographic changes at the country level. Upslope areas of each lake were determined based on the HydroSHEDS digital elevation model and geographic information system tools. After a first automatic delineation, each upslope area was corrected by hand using Google Earth.

Determinants of Water Quality in Rivers

To examine the key determinants of the pollutants of Sustainable Development Goal 6.3.2—nitrogen and salt in rivers—a similar approach is taken. Data from river monitoring stations in the GEMStat database are used to measure concentrations of nitrogen and salt in rivers. Nitrogen is measured using a combination of nitrates and nitrites, and salinity is measuring using electrical conductivity, as discussed in prior chapters. Global land is split into grid cells measuring 0.5 degrees on each side, and grid cells are matched to monitoring stations based on digital elevation models. This allows for the determination of how runoff flows off land and into rivers and is similar to the upslope area of lakes described earlier.

DETERMINANTS OF NITROGEN AND SALT IN GLOBAL RIVERS

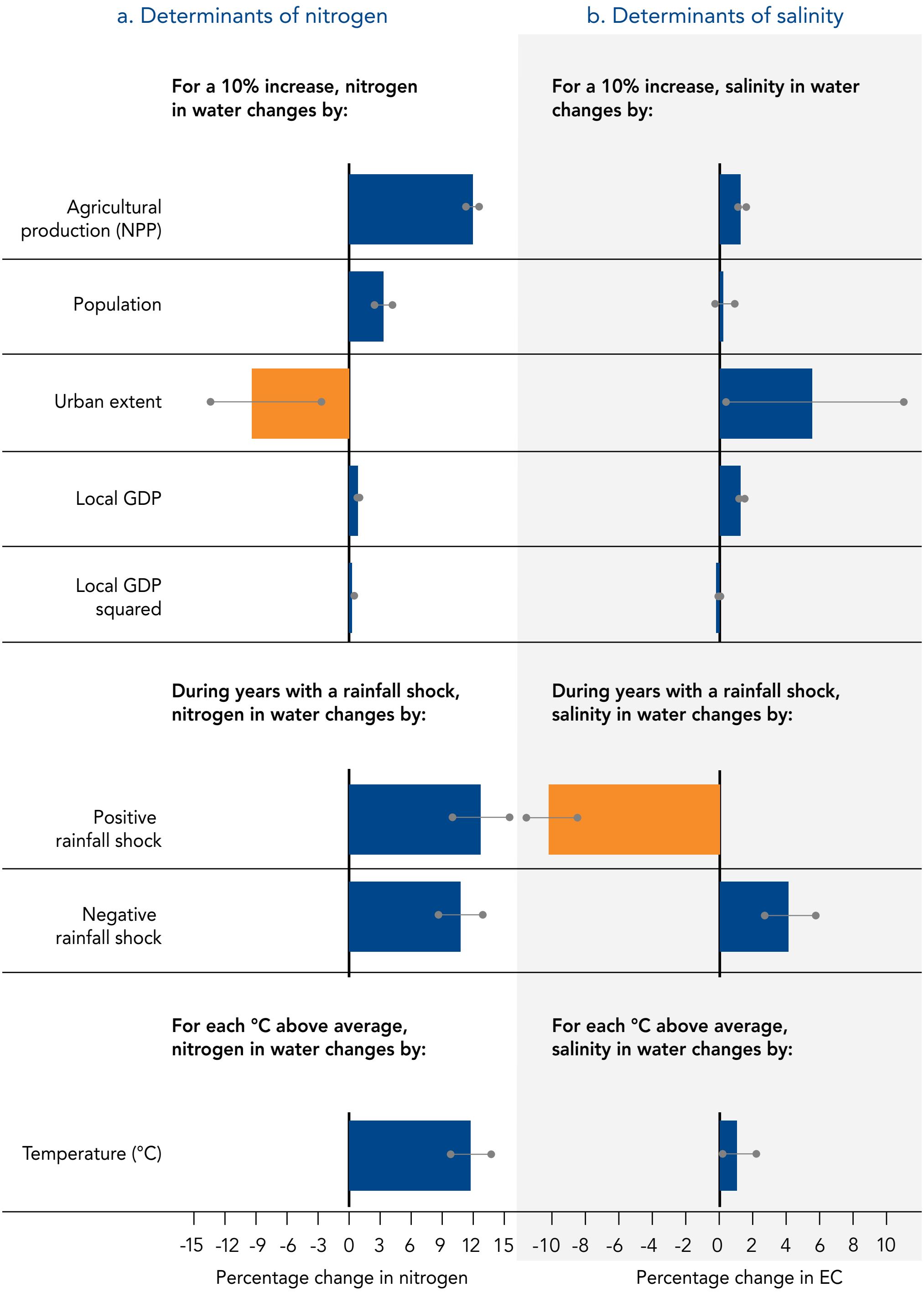
Next, the analysis turns to key determinants of the pollutants of SDG 6.3.2, nitrogen and salt, in rivers. The methodology is described in box 4.4, and figure 4.1 shows results from this global analysis. Examining first the determinants for nitrogen (in the form of nitrates and nitrites) in rivers, it is perhaps no surprise that nitrogen levels are most sensitive to agriculture. When yields of upstream crops increase by 10 percent, downstream nitrogen increases by 12.6 percent. In this specification, larger upstream populations increase nitrogen in water, not larger urban areas, although the size of the impact is relatively small.[5]

Economic activity in the form of gross domestic product (GDP) is also associated with larger levels of nitrogen in water. Both the linear and the quadratic terms are positive, which implies that as GDP increases, so do nitrogen levels, and at an increasing rate. This reflects the discussion in chapter 1 that shows that nitrogen is not a problem that can easily be grown out of. High levels of rainfall variability—in both positive and negative directions—increase nitrogen in waterways. Heavy levels of rainfall disrupt soils and wash stored nitrogen off the land into waterways. However, low levels of rainfall prevent the dilution of surface water, leading to higher concentrations of nitrogen in water even if total nitrogen is reduced. Finally, nitrogen increases with higher temperatures. This is consistent with the scientific literature, which has found that nitrification rates in water increase with temperature (Zheng, Cardenas, and Wang 2016).

The size and direction of the impact of the three weather variables are particularly concerning, given the expected impacts from climate change. Although climate models disagree on the local impacts of climate change, they converge on two global trends: temperatures will increase, and rainfall variability will increase. Thus, even if all other anthropogenic factors, such as agricultural production, land use change, and population growth, were to stabilize, nitrogen concentration in water would increase because of changing climatic factors.

Next, examining panel b of figure 4.1, it becomes apparent that salinity in water is generally not as sensitive to the same factors as nitrogen. While increased agricultural production upstream increases salinity in water downstream, the effect is low. In addition, upstream population has no statistically significant relationship with salinity. However, larger upstream urban areas increase salinity, with a 10 percent increase in urban extent increasing downstream salinity by about 5 percent. This link has been shown to occur because enhanced stormwater drainage efficiency in urban areas increases the rate of transport of salt ions from urban sources to streams. Paved surfaces also reduce the interaction between stormwater and groundwater, which causes these ions to be drained into surface waters (Hatt et al. 2004). The salting of roads in urban areas for deicing can also play a large role in increasing local salinity. Finally, increasing local economic activity is associated with higher levels of salinity. However, unlike with nitrogen, salinity does not increase at an increasing rate as GDP increases. Instead, the squared term is negative, implying that the increase in salinity slows at higher levels of economic activity.

FIGURE 4.1: Determinants of Nitrogen and Salinity in Rivers



Note: Each panel shows the results from a different regression, described in box 4.4. Error bars show the 95% confidence interval of each point estimate. EC = electrical conductivity; GDP = gross domestic product; NPP = net primary productivity.

Significant rainfall variability also impacts salinity. Large positive rainfall shocks, during which rainfall is significantly above average, reduce salinity in downstream surface waters because of greater dilution. Likewise, when rainfall levels are significantly below average for the local region, downstream salinity increases because of the lack of dilution.

THE WAY FORWARD

The analysis in this chapter highlights some key determinants of water quality and how impacts may be aggravated through unintended activities that neglect consequences for water quality. The appendix discusses how environmental water quality impacts urban areas economically through amenity pricing.

There are several critical policy insights suggested by this analysis. In general, the statistical analysis suggests that development that builds out (extensification) rather than up (intensification) may put a greater burden on water resources. Land use change for both urbanization and crop production has on average (but not always) a greater impact on environmental water quality than increases in population density or more intensive agriculture. Thus, policies that promote land conservation and protection, as well as forest management, may be the most effective at protecting water resources.

Urban expansion is inevitable, particularly in developing countries. Between now and 2050, the share of the world's population living in urban areas will increase from 55 to 68 percent. Combining this with expected population growth means an additional 2.5 billion people living in urban areas, with close to 90 percent of this increase occurring in Asia and Africa alone (United Nations 2018). Policy makers and urban planners should carefully choose sites for expansion and attempt to limit the footprint that cities have on nearby water quality. Permeable surfaces such as natural ground or pavement systems reduce urban runoff into nearby water systems, which can be contaminated by motor oils or heavy metals (Brattebo and Booth 2003). Similarly, green spaces in cities can be important sinks for water runoff. These solutions have dual benefits in that they are also important for reducing urban flooding.

The spatial planning of land development will be critical for protecting water resources. Forested areas and wetlands are important habitats for absorbing nutrients that would otherwise run into water supplies. By placing or maintaining them around the boundaries of waterways, they can act as a buffer, shielding the waterways from potential pollutants. As global populations continue to swell well into the twenty-first century, an increase in land use for both urban areas and food production is inevitable. Informed land use planning that aims to protect our precious waterways could reduce the footprint of this land use change. Indeed spatial planning that includes the use of natural buffers may well be the most effective strategy for combating some pollutants, especially in the light of evidence presented in chapter 6 on the limited effectiveness of investments in wastewater treatment in some settings.

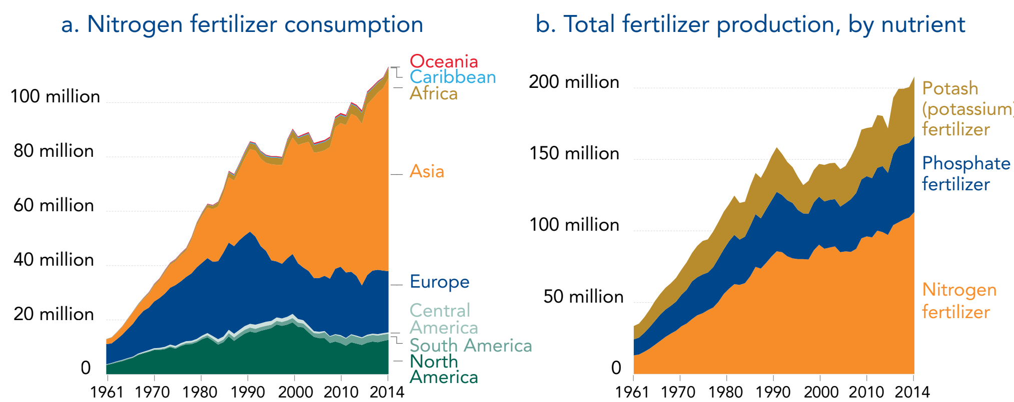
Better intensive practices of agriculture are also critical for protecting water supplies and ecosystems. Tackling and reducing large fertilizer subsidies that distort the amount of nutrients applied to fields must be another critical priority. Since the 1960s, subsidies have led to a steady increase in the production and consumption of nitrogenous fertilizers, with nearly all growth occurring in Asia (figure 4.2). Phosphorus and potassium fertilizer production rates have also been increasing, but their increase pales in comparison to that of nitrogen. This is largely because nitrogen is the nutrient most frequently subsidized. Likewise intensive animal husbandry is known to be a key factor in heavy nutrient discharges in waterways (Karr et al. 2001).

As the results of this chapter show, this massive increase in nitrogen fertilizers has left a scar across many of our world's water bodies. Because of excess use and inefficiencies in application, not all nitrogen applied on fields is absorbed by crops (box 4.5). In India, for example, only 32 percent is absorbed by plants, compared with 52 percent in Europe and 68 percent in Canada and the United States (Zhang et al. 2015).

Fertilizer subsidies are often seen as untouchable for politicians. Farmers represent large and influential constituencies in many countries, and the agricultural lobby can play a pivotal role. However, there are political and environmental win-wins in which these highly inefficient subsidies (in many countries, excess nitrogen fertilizers are counterproductive and reduce yields) can be replaced with less distorting subsidies or income support programs, thus ensuring that nobody is made worse off. Payments for ecosystem service schemes are one such example, whereby farmers can be paid to use less fertilizer. These schemes are discussed further in chapter 6.

Another way of controlling nutrient pollution from nonpoint sources like farms is through pollution trading. Trading schemes allocate nutrient

FIGURE 4.2: Nitrogen Fertilizer Consumption and Production, 1961–2014



Sources: Food and Agricultural Organization of the United Nations FAOSTAT database: http://www.fao.org/faostat/en/#data/RA; Roser and Ritchie 2019.
Note: Panels show the consumption of nitrogen fertilizer in tons across regions (panel a) and the global production of nitrogen, phosphate, and potash fertilizer (panel b) in tons per year.

BOX 4.5: Fertilizer Application—Skewed and Distorted

In general, the optimal application of fertilizers requires that the proportions of nitrogen (N), phosphorus (P), and potassium (K) (in its water-soluble form, potash) be balanced. An N:P:K ratio of 4:2:1 is generally considered an acceptable benchmark of fertilizer mix. While the correct proportions are driven by the type of crop, soil, and other agronomic conditions, measuring deviations from the recommended ratio can reveal the extent of distortion. Table B4.5.1 presents distortions from the optimal N:P and N:K ratios (with respect to N).

TABLE B4.5.1: Distortions from the Optimal Nitrogen-to-Phosphorus and Nitrogen-to-Potassium Ratios

Location	N (kg/ha)	P (kg/ha)	K (kg/ha)	N:P distortion[a]	N:K distortion[b]
World	68.75	29.47	23.76	33%	−28%
United States	79.06	27.04	29.23	92%	−32%
India	99.99	37.60	14.86	66%	68%
China	253.62	127.02	110.34	0%	−43%
Brazil	44.72	54.88	62.30	−119%	−82%
Bangladesh	144.75	66.46	40.73	18%	−11%
Vietnam	136.15	57.89	54.88	35%	−38%

Source: Food and Agriculture Organization of the United Nations.
Note: ha = hectare; K = potassium; kg = kilogram; N = nitrogen; P = phosphorus.
a. Percentage change from optimal amount of N relative to P multiplied by 2.
b. Percentage change from the optimal amount of N relative to K.

In many of these countries, fertilizer use is disproportionately tilted toward the use of nitrogen. Oftentimes, the structure of fertilizer subsidies contributes heavily to such a skew. In India, this skew is particularly striking in favor of nitrogen, where fertilizer subsidies heavily support nitrogen over other nutrients, resulting in an inefficient balance of fertilizer application (Chatterjee and Kapur 2017; Gulati and Banerjee 2015). By 2015, subsidy costs had soared to US$11.6 billion per year in India, roughly five times more than what was recorded 15 years earlier (Gulati and Banerjee 2015). This is exemplified by the yawning gap between global and Indian domestic nitrogen prices—world prices were almost four times higher than regulated Indian prices in 2014 (Huang, Gulati, and Gregory 2017). As a result, application ratios in India are 8:3:1, with adverse long-term impacts on soil fertility and crop yields (Huang, Gulati, and Gregory 2017).

emissions across multiple users, allowing them to trade licenses to emit nutrients into the environment on established markets. Agents who are less productive nutrient users often find that it is more profitable to sell their pollution allocations to more productive agents than to use them. Thus, trading schemes have the potential to lead to economically efficient outcomes while also limiting total nutrients released into the environment.

The drawback of such schemes is that they often require complex designs. Multiple heterogeneous pollutants (for instance, nitrogen and phosphorus) must be tracked from multiple emission sources to multiple end points. Interactions among these pollutants can change how they impact water resources, as can external factors like weather, landscape, and anthropogenic activities (Shortle and Horan 2017). Thus, establishing the total amount of nutrients that the trading scheme should permit is difficult. Transaction costs in establishing and participating in markets, as well as complexities in calculating emissions and abatement, make monitoring and enforcement difficult. Therefore, pollution trading schemes are currently relegated to high-income countries like Canada, New Zealand, and the United States where the capacities of regulatory bodies are higher. Even still, most of these schemes have seen little pollution trading thus far (Fisher-Vanden and Olmstead 2013; Ribaudo and Gottlieb 2011) implying either overallocation of nutrient emissions or difficulty in establishing markets. Thus, more work is needed to design systems that are not simply efficient from an economic standpoint but also can manage all of these complexities while remaining feasible in developing country settings and encouraging trading between agents.

Finally, an important lesson of this chapter is the impact that climate change will have on water quality. Both nitrogen and salinity in water are significantly affected by rainfall variability. With climate change expected to increase variability in most regions across the world, the impact on water quality is an important challenge that is often overshadowed by water scarcity and flooding. In addition, hotter temperatures increase biological growth when nitrogen is present, leading to more frequent and cyanobacterial and algal blooms.

Some solutions already discussed will help protect water resources from the impacts of climate change. Reducing the footprint of urban areas and impervious land will prevent nutrients and salts from washing off the land and into waterways. Similarly, with less nitrogen spread on farmlands, there will be less to run into lakes and rivers.

When water levels are low because of dry rainfall shocks or prolonged droughts, nutrients and salts in water are less diluted and therefore more harmful. Thus, it is important to manage water supplies to ensure water levels remain high enough to dilute expected pollutants during times or low rainfall or runoff. Infrastructure can play an important role in regulating water supplies, storing water during times of plenty and releasing it when the environment turns dry. However, demand management and reducing overextraction also need to play a critical role.

NOTES

1. These algal blooms have sparked an environmental movement in Toledo, Ohio, a city on Lake Erie. In 2019 a ballot measure was passed to grant the lake legal rights, which are typically reserved for people (Daley 2019). As of this writing, the legislation is being challenged in the courts.
2. www.worldbank.org/qualityunknown.
3. Cyanobacteria technically are not algae, although they are often called such. They are prokaryotic bacteria (simple organisms lacking a nucleus, mitochondria, and other cellular organelles), as opposed to algae, which are eukaryotic organisms (a more advanced organism with more complex cells). Nevertheless, both algae and cyanobacteria derive their energy through photosynthesis and often appear together.
4. Data were generated for 461 lakes, but 51 lakes deemed to be alkaline were removed from the analysis.
5. Agricultural land was excluded from the regression, because there was insufficient variation in this variable to identify a coefficient.

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CHAPTER FIVE

EMERGING POLLUTANTS, EVERLASTING CONCERNS

MICROPLASTICS AND PHARMACEUTICALS

Plastics. There's a great future in plastics. Think about it.

—Mr. McGuire, *The Graduate*

KEY POINTS

- Pollutants of emerging concern, such as plastics and pharmaceuticals, exemplify the wicked nature of water quality issues: they are complex and multifaceted, have no single solution, and attract divergent views from different stakeholders.
- Although far fewer data are available on freshwater plastic pollution compared with marine systems, existing studies highlight that plastics, including microplastics, are ubiquitous throughout all freshwater systems.
- Although awareness of the issues related to these two pollutants is growing, there is a severe lack of data on the scale and scope of the problem and thus limited evidence on impacts.
- Optimal and efficient solutions to date are uncertain. Even when technology exists, removing pharmaceuticals and micro- and nanoplastics from water is costly and at times nearly impossible. Thus, prevention is key, as is a better understanding of the drivers of contamination from this heterogeneous group to clarify entry pathways into aquatic environments and define reliable methods for exposure and hazard assessment.

This chapter presents the current state of knowledge on pollution caused by two of the world's most transformative discoveries: plastics and pharmaceuticals. Their use has permeated many aspects of our daily lives, but their impact on the environment is of growing concern and has captured the attention of citizens, scientists, and policy makers alike. The issues related to these pollutants are multidimensional, spanning a spectrum of challenges from environmental sustainability to food security and human health. Although current scientific evidence about their impacts on ecosystems and humans is uncertain, there is no doubt that pollution from plastics and pharmaceuticals remains an emerging and growing concern.

PROFUSION OF PLASTICS

Rivers have always represented an easy way to dispose of waste: throw it in the river, and it flows downstream and becomes someone else's problem. When populations were smaller, and most waste was biodegradable, this did not cause much of a problem. Today, however, the banks of many of the smallest streams and the greatest rivers are clogged with trash, much of it composed of plastic, which does not break down easily or in an environmentally friendly way.[1] Although this trash may be an eyesore, what we do not see may be even more harmful.

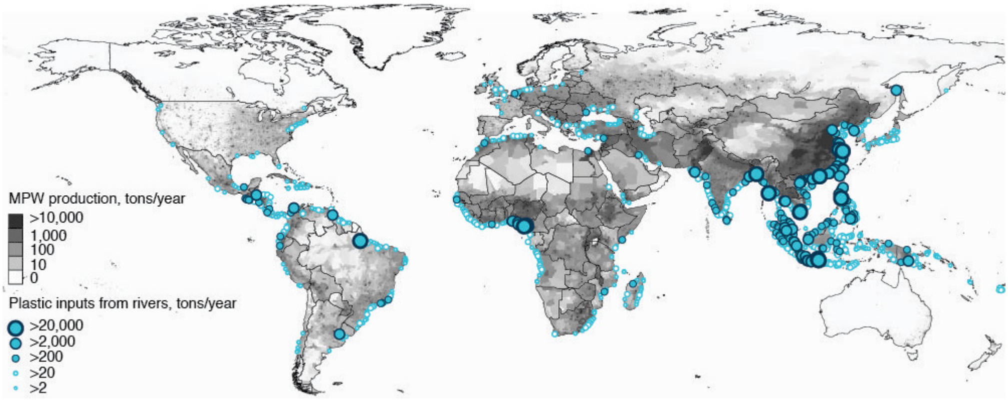
THE PROBLEM

Since the 1950s, humankind has produced 8.3 billion tons of plastic, of which 91 percent has not been recycled (Geyer, Jambeck, and Law 2017). In coastal regions alone, it is estimated that between 4.8 and 12.7 million tons of mismanaged plastic waste each year end up in oceans (Jambeck et al. 2015). Each year, millions of tons of plastic waste enter the ocean from rivers, with the top 20 polluting rivers, mostly located in Asia, accounting for 67 percent of global riverine emissions (map 5.1) (Lebreton et al. 2017).

Although it will take centuries or even millennia for this waste to degrade, the plastics will slowly degrade to increasingly smaller pieces. While there is uncertainty about the extent of the problem, recent studies have detected microplastics—defined as pieces that are smaller than 5 millimeters in length, roughly the diameter of a grain of rice—in 80 percent of global freshwater samples (Tyree and Morrison 2017), 81 percent of municipal tap water samples (Kosuth, Mason, and Wattenberg 2018), and even 93 percent of bottled water samples (Mason, Welch, and Neratko 2018), as well as on remote mountain locations where they are carried by rain (Allen et al. 2019).

Microplastics are conjectured to have life spans of hundreds to thousands of years (Barnes et al. 2009; Thompson et al. 2005) and have been found in

MAP 5.1: Mass of River Plastic Flowing into Oceans



Source: Lebreton et al. 2017. Reproduced under Creative Commons license 4.0 International (CC BY 4.0). http://creativecommons.org/licenses/by/4.0/. Further permission required for reuse.
Note: MPW = mismanaged plastic waste.

the remotest parts of the planet, from pristine islands and high mountain lakes to remote deserts (Lavers and Bond 2017; Zylstra 2013). There is no single source of microplastics; they are not all made from the same material, and they do not have the same properties. Clothing made from synthetic fabrics, tire dust, plastic cutlery, paints, cosmetics, and degradation of larger plastic debris items are major contributors to the microplastics problem. Wastewater treatment plants can act as emission pathways, aggregating particles left untreated and depositing them in rivers or wetlands (Burns and Boxall 2018; Tyree and Morrison 2017; Wagner and Lambert 2018). Currently, more than 5,300 grades of synthetic polymers (plastics) are used in commerce (Wagner and Lambert 2018). These polymers have different properties, rendering their transport, degradation, ingestion, and contaminant release complex (Bakir, Rowland, and Thompson 2014; Endo et al. 2005).

As the particles become smaller with fragmentation of larger plastics, the situation becomes more complex and knowledge becomes sparser. Nanoplastics, for example, are particles that are smaller than 1 micrometer in diameter, so small that they cannot be seen under a standard microscope or detected in water with widely available tools. Once in the aquatic environment, the transport and degradation of plastics generate a mixture of micro- and nanoparticles, leached additives, and other nonpolymer degradation products. Accordingly, biota are exposed to a complex mixture of plastics and plastic-associated chemicals that change in time and space (Wagner and Lambert 2018).

Awareness about the problem of plastics has begun to seep into public consciousness. Award-winning pictures[2] and evidence of oceanic wildlife, big and small, being smothered by plastic debris have been particularly instrumental in exposing the dark side of plastics.

UNCERTAINTY OF IMPACT

Still, for all the increased attention to microplastics, there is limited evidence about its ecological and human health impacts (box 5.1). Plastics come in diverse forms and contain a range of chemicals—pigments, ultraviolet stabilizers, water repellents, flame retardants, monomers such as bisphenol A, and plasticizers such as phthalates—that can leach into their surroundings. Some of these chemicals are considered endocrine disruptors—that is, chemicals interfering with the hormone system. Others have potential carcinogenic properties.

In the environment, plastics can have adverse effects on animals via both physical (entanglement and gastrointestinal blockage) and chemical toxicity. One major concern is that plastic particles become more toxic with decreasing size. Previous research on engineered nanoparticles (ENPs), such as those found in sunscreen, has shown that ENPs can translocate across cellular membranes.[3] Once inside the cells, they are stored inside vesicles and mitochondria and can trigger a range of cellular reactions.[4] A deeper understanding of the relationships between these cellular-level responses and population-level impacts can help determine the broader implications for ecosystem functioning.

In the case of human health, scientific evidence about the toxicity of these particles is still in its infancy. According to the latest report by Science Advice for Policy by European Academies, which forms part of the European Commission's Scientific Advice Mechanism, most studies looking at environmental toxicity have so far simulated conditions that do not reflect real-world exposure. For human health, even less is known. Further research is required to understand the effects of different sizes, shapes, and types of plastic before robust conclusions about real risks can be drawn (Science Advice for Policy by European Academies [SAPEA] 2019). This is particularly true for nanoplastics, for which much remains unknown. Yet there are reasons to be concerned as evidence emerges about the widespread occurrence of plastics in the human food chain, notably through seafood and salt (box 5.1).

PHARMAFICATION OF WATER SUPPLIES: A PRESCRIPTION FOR DISASTER

Pharmaceutical drugs are another emerging risk for global water supplies. In recent decades, the use of pharmaceutical drugs has exploded worldwide—a direct result of rising global prosperity. Between 2000 and 2015, antibiotic consumption alone increased 65 percent, reaching 34.8 billion daily doses. Nearly all this increase occurred in low- and middle-income countries (Klein et al. 2018).

BOX 5.1: Impact, Pathways, and Scope of Microplastic Pollution

Various studies have reported the prevalence of microplastics in remote uninhabited pristine islands and oceans (Lavers and Bond 2017; Zylstra 2013). But the link to human health has been difficult to ascertain, even if there is consensus that such contamination cannot possibly be good for human health.

Freshwater sources remain a major route of microplastic delivery to humans, either through direct consumption or through the food chain (Desforges, Galbraith, and Ross 2015; Güven et al. 2017; Van Cauwenberghe et al. 2015). The consequences to human health remain uncertain to date but will benefit from ongoing data gathering (Revel, Châtel, and Mouneyrac 2018; Rist et al. 2018; Schirinzi et al. 2017; Wright and Kelly 2017). A study of water samples from 11 globally sourced brands of bottled water found that 93 percent of the water samples showed some sign of microplastic contamination (Mason, Welch, and Neratko 2018). Similarly, in water samples collected globally, 80 percent of the samples tested positive for the presence of plastic fibers (Tyree and Morrison 2017). In addition, small plastic particles have been observed in the digestive tracts of more than 690 marine species (Carbery, O'Connor, and Palanisami 2018). As a result, there is growing concern about trophic transfer of microplastics in marine food webs (Browne et al. 2008; Farrell and Nelson 2013; Setälä, Fleming-Lehtinen, and Lehtiniemi 2014).

Although current scientific evidence about the harmful effects of plastics remains uncertain, there are reasons to be concerned. For instance, one hypothesized pathway is for the smallest particles to pass through cell membranes of aquatic animals and mammals, where they can negatively affect the animal's health (Dhawan, Pandey, and Sharma 2011; Wright, Thompson, and Galloway 2013). A study by Rochman et al. (2013) reported hepatic stress in fish because of the ingestion of plastic and transfer of hazardous chemicals. There are also reasons to believe that microplastics may carry microbes, including some pathogens, across large distances and, in turn, become agents of contamination in areas of high population density and low wastewater treatment infrastructure (Lu et al. 2019).

There are at least three ways that pharmaceuticals can enter the environment. The most common is through excretion in human or animal urine and feces. After intake, as much as 30 to 90 percent of most antibiotics can be excreted as active substances (Silva et al. 2015). Improper disposal of drugs is also a common way for pharmaceuticals to enter the environment. Many people will dispose of drugs in the toilet or sink, where they will either end up in sewage treatment plants, which are often not equipped to remove these pollutants, or be released directly into the environment, which is more common in developing countries with inadequate infrastructure (Owens 2015). Finally, some drug manufacturers release their active ingredients directly into waterways. Wastewater treatment plants serving a large drug-manufacturing region in Patancheru, India, were found to have concentrations of the antibiotic ciprofloxacin 1,000 times the level toxic to some bacteria (Larsson, De Pedro, and Paxeus 2007).

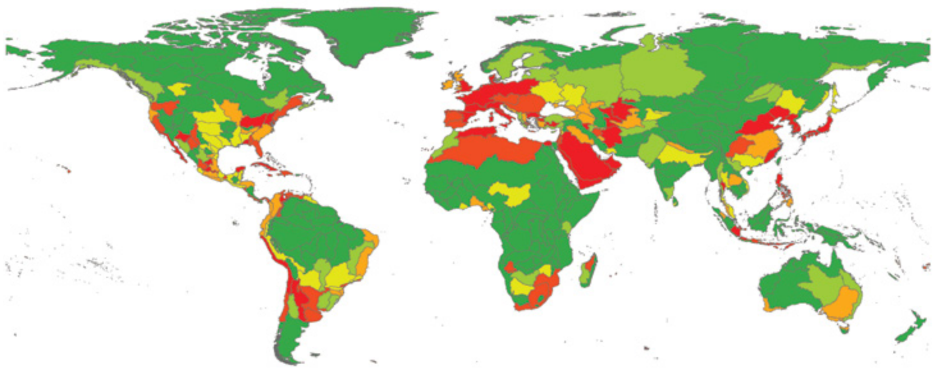
So what impact do these drugs have on environmental and human health? That is still hard to fully quantify. The concentrations found in waterways are often lower than typical doses, and very low dose consumption over time will have different impacts than standard doses. However, there is emerging evidence of impacts. Some animal species can be sensitive to these drugs. In India, *Gyps* vultures have been driven to near extinction because of contamination of their food supply with the anti-inflammatory drug diclofenac (Weber et al. 2014). Antidepressants have been shown to negatively affect reproductive behavior in clams and change behavior in cuttlefish and crayfish (Lyons 2014). In addition, the active ingredient in contraceptive pills has driven some fish populations in Canada to near extinction (Kidd et al. 2007).

Antimicrobial drug resistance to waterborne and water-related diseases such as salmonellosis (Threlfall 2002), *Escherichia coli* infections (Nys et al. 2004), shigellosis (Niyogi 2005), cholera (Kitaoka et al. 2011), and campylobacteriosis (Luangtongkum et al. 2009) is widely reported. The extent of antimicrobial resistance is alarming and has been a cause of concern for more than 20 years. For instance, a survey by Bennish (1994) in Bangladesh showed that resistance to the antibiotic tetracycline among cholera strains rapidly increased from 1.9 percent in 1990 to 85.4 percent in 1993, and 90.0 percent of isolates were resistant to key antibiotic treatment using tetracycline, ampicillin, and trimethoprim-sulfamethoxazole. According to the World Health Organization (WHO 2017b), lack of government commitment to address the issues, poor surveillance, and dwindling diagnostic resources to treat and prevent disease have hindered the control of antimicrobial drug resistance.

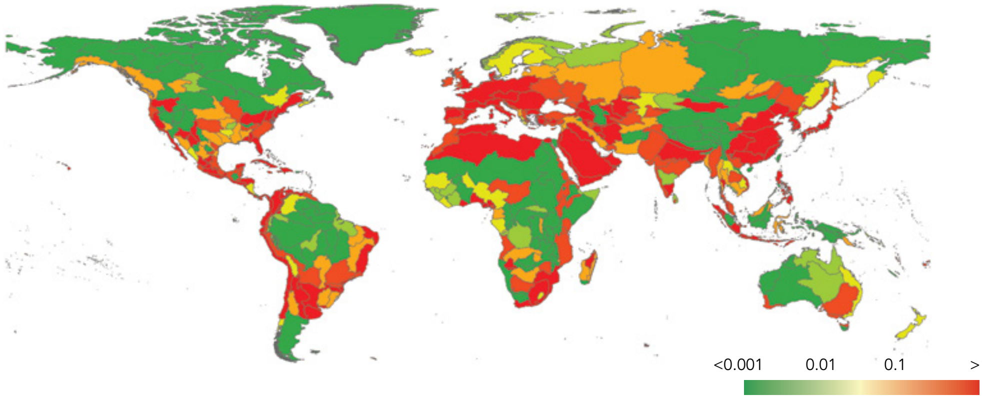
With regard to human impacts, one of the greatest current risks is the increasing prevalence of antimicrobial resistance—the ability of microbes to grow in the presence of antibacterial, antiviral, antiparasitic, and antifungal drugs that would normally kill or limit their growth (National Institute of Allergy and Infectious Diseases [NIAID] 2009). Antimicrobial resistance occurs naturally over time through genetic changes and the natural selection process. However, the introduction of antibiotics into natural environments accelerates this evolution, threatening the effective prevention and treatment of a range of infections.[5] A new global study on pharmaceuticals in the environment found that between 1995 and 2015, aquatic exposure to the antibiotic ciprofloxacin has proliferated throughout the globe (map 5.2) (Oldenkamp, Beusen, and Huijbregts 2019).

MAP 5.2: Risk Maps for Antibiotic Ciprofloxacin, 1995 and 2015

a. 1995



b. 2015



Source: Oldenkamp, Beusen, and Huijbregts 2019.
Note: Maps show aquatic risks per ecoregion from ciprofloxacin in 1995 (top) and 2015 (bottom). Legend shows the ratio of predicted environmental concentrations in waterways to the no-effect concentration. Thus, values greater than 1 imply that predicted environmental concentrations are above the levels at which one would expect to start seeing effects.

The management of the leading causes of disease and death in the developing world (gastrointestinal, respiratory, and sexually transmitted infections) is critically compromised by the rapid spread of antimicrobial resistance (Okeke et al. 2005). Increasing rates of resistance are reported in bacteria around the world (Antoniadou et al. 2007; Baadani et al. 2013; Capone et al. 2013; Ko et al. 2007; Kontopidou et al. 2011; Napier et al. 2013). Antimicrobial resistance also has significant impacts on the cost of health care because of longer hospital stays and increased costs of medication and procedures (such as laboratory, radiology, and bronchoscopy), in addition to the indirect costs of lost production because of reduced working time (McGowan 2001). Currently, 700,000 people die each year from drug-resistant infections, which is seven times as many as die from cholera. It is estimated that if action is not taken, by 2050 that number could reach 10 million people and cost an estimated US$100 trillion (O'Neill 2016).

SOLUTIONS REMAIN ELUSIVE

There are no simple solutions to solving the problem of plastics and pharmaceuticals. Scientific evidence about the impacts is only now emerging. Yet it is clear that even if the impacts are uncertain, the current evidence on possible harm to ecosystems and humans is an urgent call to forestall the problem and prevent it from growing further.

PLASTICS

Hundertmark et al. (2018) predicted that if the demand for plastics follows its current trajectory, global waste volumes would grow from 260 million tons per year in 2016 to 460 million tons per year by 2030, taking what is already a serious problem to a new level. International bodies recognize this problem. The United Nations Environment Programme (UNEP) recognized the release of plastic materials into the environment as an emerging environmental pollution issue in 2011 (UNEP 2011). However, currently no standard method of measurement for microplastics exists, and few protocols on laboratory methods for the analysis of microplastics in the marine environment and urban rivers are available (Masura et al. 2015; McCormick et al. 2014). Still, it is clear that wastewater treatment plants must play a bigger role in removing plastics from rivers. Although many micro- and nanoparticles are too small to be filtered out, removing larger pieces of plastic is important for prevention of the problem.

Better environmental regulations around plastics are also needed. A notable civic movement against microbeads is the Beat the Microbead campaign, which started in 2012. The movement asks producers for a commitment to ensure that their cosmetics are free of microplastic ingredients and awards participating companies with the use of the Beat the Microbead campaign's Look for the Zero logo. Perhaps in reaction to the attention that the movement has brought to the issue, several countries and economies began passing regulations against microbeads, including the U.S. Microbeads-Free Waters Act of 2015, Canada's recent classification of microplastic ingredients as toxic, and bans on microbeads in France; Taiwan, China; and the United Kingdom in 2018. The European Union has a plastics strategy that recommends the monitoring of microplastics in drinking water, an issue echoed in the revision of the Drinking Water Directive. Similarly, many local governments and even some countries have begun banning or taxing single-use plastic bags (also known as disposable carryout bags) and plastic drinking straws and utensils. While they signal a needed awareness, the single-issue focus can have unintended leakages, with increased consumption of products banned in some countries appearing in unregulated parts of the globe (Fowlie 2009).

Accordingly, new research finds that in California, the elimination of 40 million pounds (approximately 18.1 million kilograms) of plastic carryout bags was offset by a 12-million-pound (approximately 9.5 million kilograms) increase in trash bag purchases. This highlights the need for a comprehensive approach to the plastics challenge, as adopted by the European Union in its European Strategy for Plastics in a Circular Economy (January 2018), which targets plastics from their design to production, use, and recycling.

Modeling by Hundertmark et al. (2018) suggests that plastic reuse and recycling could become a profitable enterprise and generate profits of US$60 billion for the petrochemicals and plastics sector. But this is unlikely to occur without the right policies and regulations in place to incentivize better stewardship. There is also the threat of unintended consequences. The literature on voluntary approaches to environmental problems is comprehensive and conclusive. It suggests that companies are unlikely to engage in costly pollution reduction without regulations, monitoring, and enforcement, even when there is a background threat of stricter future regulation. Empirical analyses indicate that voluntary approaches have generally failed to deliver on the anticipated promise (Blackman et al. 2013; Borck and Coglianese 2009; Khanna 2001). There is emerging evidence that in the absence of regulation of plastics, recycling is likely to be limited. For instance, China's July 18, 2017, World Trade Organization filing that banned dozens of scrap categories upended recycling economics around the world. Before the ban, China imported two-thirds of the world's plastic waste.[6] The ban has made plastic recycling costlier and led to much of it ending up in landfills or simply being burned in vast volumes, directly threatening air and water quality.

As demand for plastics continues to grow worldwide, the imperative to put in place an effective system becomes more pressing. Going forward, the plastics problem requires a more comprehensive approach that carefully weighs the uncertain local and global economic impacts against the costs of reducing pollution loads. If there is an opportunity to be made out of reduction, reuse, and recycling of plastics, it is most likely to occur when governments establish the right incentives to make environmental stewardship more profitable.

Plastics are at the tip of a highly visible iceberg and a powerful force to mobilize public opinion. Images of plastic waste across the globe have contributed to raising global awareness—what is missing is a clear policy framework and strategy to chart the way forward.

PHARMACEUTICALS

As is the case with plastics, pharmaceuticals are critical to modern life and will not be going away any time soon. A world where antibiotics are made less effective by antimicrobial resistance would be a problem on many fronts. Yet there are no easy solutions to the pharmafication of water. Nevertheless, recently there has been growing recognition of the need for arrangements and rules aimed at diminishing use of antimicrobial drugs. The most obvious priorities are the need to control misuse in animal husbandry and safe disposal of unused medication.

Intensive animal farming has taken a heavy toll on the environment and carries a large water footprint and carbon footprint—and now we learn also a large pharmaceutical footprint. In some countries, approximately 80 percent of total consumption of antibiotics is in the animal sector, and much of this is consumed by healthy animals (WHO 2017b). In 2017, WHO issued guidelines on the use of medically important antimicrobials in livestock, which includes a set of guidelines and best practices that livestock raisers should follow.

For human antibiotics and other pharmaceuticals, the urgent need to address the issue is growing with the increase in consumption. Klein et al. (2018) show that between 2000 and 2015, antibiotic consumption, expressed in defined daily doses (DDDs), increased by 65 percent (21.1–34.8 billion DDDs), and the antibiotic consumption rate increased by 39 percent (11.3–15.7 DDDs per 1,000 inhabitants per day), an increase driven by low- and middle-income countries. Controlling consumption of medicines will likely be a slow process involving education, information, and behavior change among consumers, medical service providers, and the pharmaceutical industry. Takeback programs involving both public authorities and manufacturers that can safely manage unwanted, unused, or expired medication at risk of being disposed of directly into waterways or indirectly through waste and landfills can help limit the quantity of harmful waste. Early experiments in the United States and Australia suggest there is scope for expanding this approach in the short run.

Finally, greater responsibility must be placed upon the manufacturers of antibiotics and other pharmaceuticals to contain this growing problem. As discussed earlier, some regions that are hotspots for drug manufacturing are also hotspots for pharmaceutical water contamination. Too often, under the guise of drug donations, pharmaceutical companies ship their expired medications to developing countries that are unprepared to manage their disposal. Worse, international law prevents countries from returning these donations to donors, because they are often considered hazardous cargo (Pinheiro 2008). Thus, there is a case to be made for the international community to put together regulations and oversight, on an industry that was worth more than US$934 billion in 2017 and is expanding,[7] to prevent practices from irresponsible actors.

NOTES

1. There is no environmentally friendly process of degradation. Even biodegradable plastics leach chemicals and generate microplastics.
2. Photographer Justin Hofman, behind the powerful and poignant image of a seahorse swimming with a discarded cotton swab, was a finalist in the 2017 Wildlife Photographer of the Year competition from the Natural History Museum in London.
3. ENPs are distinct from nanoplastics in that ENPs are mostly made of metals for specific purposes (e.g. titanium dioxide particles in sunscreen).
4. Cellular responses include oxidative stress, antioxidant activity, and cytotoxicity.
5. Key facts about antimicrobial resistance from WHO: https://www.who.int/news-room/fact-sheets/detail/antimicrobial-resistance.
6. China's new policy could displace as much as 111 million tons of plastic waste by 2030. *National Geographic*, June 2018. https://news.nationalgeographic.com/2018/06/china-plastic-recycling-ban-solutions-science-environment/.
7. The Growing Pharmaceuticals Market: See https://blog.marketresearch.com/the-growing-pharmaceuticals-market-expert-forecasts-and-analysis.

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CHAPTER SIX

POLICIES TO TAME A WICKED PROBLEM

Then such waters as flow to the rising sun, must necessarily be clear, fragrant, soft, and delightful to drink.

—Hippocrates: *On Air, Water, and Places*

KEY POINTS

- Water quality is a wicked problem: impacts, sources, and the scale of the problem are all uncertain with solutions that are often elusive.
- Only three options are available to address the water quality problem: prevention, treatment, and information provision.
- The limited available evidence suggests that in much of the developing world, where enforcement capacity and resources are limited, these policy tools are not always effective at addressing the problem.
- Emerging technologies such as remote sensing, machine learning, and blockchain can help overcome many of these enforcement constraints and offer new possibilities when capacity is limited.

A WICKED PROBLEM

Previous chapters have argued that understanding of the impacts of water quality on human health and the environment remains incomplete and uncertain. Much is unknown at every step of the process—from the generation of pollutants, to their measurement, to assessing impacts, to the elusive quest for solutions. Levels of uncertainty are significantly greater for emerging pollutants such as microplastics and pharmaceuticals associated with microbial resistance, as well as those causing neuroendocrine disruption, such as vinyl chloride (World Health Organization [WHO] 2004) and estrogen (Adeel et al. 2017). There is also limited knowledge of the cumulative impacts of a mix of contaminants. It is theoretically possible that combinations of pollutants have additive, synergistic, and antagonistic interactions and impacts. However, little is known about combined impacts (Stoiber et al. 2019). As a result, WHO recommends a gradual and iterative approach (WHO 2017a):

> The detection of [microbial and chemical] constituents … is often slow, complex and costly, which limits early warning capability and affordability. … As it is neither physically nor economically feasible to test for all … parameters, the use of monitoring effort and resources should be carefully planned anddirected at significant or key characteristics.

Measuring, understanding, and regulating water quality combine the ingredients of a “wicked problem,” a term coined by design theorists Horst Rittel and Melvin Webber in 1973 to describe complex problems with no optimal solution. Solutions to wicked problems are ill defined; worse still, a solution in one place or moment in time may yield different results in another and may create new problems (Rittel and Webber 1973). In addition, even when experts agree on the best action to take, achieving the political will to implement and maintain that action is challenging (box 6.1). Therefore, the harmful effects of water pollution persist around the world, despite established policies and regulations to reduce pollution and significant investments in pollution control and treatment.

THE TOOLBOX: THREE MAIN APPROACHES

Faced with these complex challenges, there are three broad approaches to the water quality problem available to policy makers (figure 6.1):

- Policy inaction is not uncommon in low-income countries or where there is uncertainty about the effects of pollutants. Responses to perceived hazards are then left to individuals, who may, for instance, relocate to a safer area or circumvent the effects through private avoidance actions.

- Policy makers may be proactive and seek to prevent or reduce pollution at its source.

BOX 6.1: Politics and Progress of Water Quality Regulation

Even when science suggests where safe thresholds might lie, and reliable measurements are available, political inertia remains a significant barrier to policy action.[a] Both targets and choices of policy instruments are political decisions. For instance, in the United States, the first federal law dealing with water quality—the Water Pollution Control Act of 1948—was preceded by more than 100 similar bills defeated between 1902 and 1948 (Melosi 2000).[b] The 1948 act proved to be an ineffective piece of legislation, exemplifying the difficulties of addressing water quality problems. It was not until after the passing of the 1972 amendment known as the Clean Water Act, which gave the U.S. Environmental Protection Agency (EPA) the authority to implement pollution control programs and set discharge standards, that the problem was deemed to have been brought under control. Even so, in 2015 alone, as many as 21 million Americans may have been exposed to unsafe drinking water (Allaire, Wu, and Lall 2018), indicative of a wicked problem (Plumer and Popovich 2018).

a. With the goal of reducing the risk of waterborne contamination from fecal pathogens largely accomplished by the early 1940s, more attention began to be paid to improving conditions in rivers. The U.S. Geological Survey began regularly collecting and publishing water quality data from streams around the nation, reflecting the increased emphasis on water quality. However, attempts to improve water quality standards were largely set aside during World War II because of the need to increase wartime industrial production (Murphy 1961).

b. By most measures, the 1948 Water Pollution Control Act was an ineffective piece of legislation that had little impact on water pollution in the United States, even though it was the first federal attempt to deal with overall water pollution. The importance of this act stems from it laying the foundation for a series of improvements ultimately resulting in the 1972 Clean Water Act. As passed in 1948, the Water Pollution Control Act was limited to interstate waters—those that crossed or formed state borders—and authorized the surgeon general to focus only on pollution that endangered the "health or welfare of persons in a State other than that in which the discharge originated" (Milazzo 2006). Enforcement of the law was left to the states, and the surgeon general could only initiate federal involvement if the polluting state agreed. As a result, in eight years of existence, not a single pollution abatement order was issued under the 1948 law (Milazzo 2006).

FIGURE 6.1: Three Main Approaches to the Wicked Problem

1. PASSIVE	2. PROACTIVE	3. REACTIVE
Policy inaction	Prevent, abate, or mitigate	Treat or purify

- Alternatively, they may be reactive and attempt to treat the toxic discharges, typically through investments in various types of water treatment facilities.

POLICY INACTION

When governments lack information about the impact of a pollutant on health or the environment—as with nanoplastics or where public funds and enforcement capacity is limited—responses are often left to individuals. For example, individuals may invest in private groundwater wells, purchase water filters, buy bottled drinking water, or relocate from polluted water to avoid local disamenities—if they can afford to do so.

In these cases too, there is an important role for government to provide better information to consumers about the known and uncertain risks. This would allow consumers to decide how best to respond to the risks. Disclosure may also affect consumers' demands of polluting companies, when the source of pollution can be identified, and the enterprise may be goaded by consumer concerns into improving environmental performance. For instance, this was the strategy used with some success in Indonesia's Program for Pollution Control, Evaluation, and Rating (PROPER). Factories were color rated to indicate performance (black, red, blue, green, or gold, where black labels represented the worst performers and gold labels the best performers). There is consensus that PROPER did reduce firm pollution emissions, especially for low-compliance firms engaged with global enterprises. Information disclosure can also help in galvanizing public opinion to create the political support needed for policy action.

PROACTIVE APPROACHES: PREVENTION

Proactive approaches that are designed to prevent, reduce, or eliminate pollution include an array of regulatory instruments that either mandate or incentivize polluters to reduce waste at the source by modifying production processes, promoting the use of less toxic inputs, improving efficiency, and reusing materials. A clear advantage of this approach is that there is less waste to control, treat, or dispose and, as a result, a lower risk to public and environmental health. It is also the preferred approach where treatment of waste is exceptionally costly or the public hazards associated with the pollutant are deemed to be exceptionally high or uncertain.

As the adage goes, an ounce of prevention is often better than a pound of cure. Accordingly, prevention is the safer, and often cheaper, alternative. But it requires that governments have the capacity to enforce rules and create incentives for polluters to comply with regulations to lower emissions. This in practice has been challenging in almost all developing countries, because they lack the capacity to enforce laws.

Preventative approaches can take various forms, including command and control rules that mandate allowable levels of pollution or technologies and policies that create incentives to reduce pollution, such as a pollution tax, a subsidy to lower emissions, or a pollution trading scheme. Most common in developing countries is the use of command and control mandates that decree either a maximum level of allowable pollution or a technology standard (box 6.2). Incentive-based instruments tend to be less common in developing countries.[1]

BOX 6.2: Examples of Pollution Regulations in India and Vietnam

India's National River Conservation Plan (NRCP) is an example of a prescriptive approach to water pollution control. The NRCP, starting in 1985, established a set of designated uses for surface waters and prescribed a set of approaches for achieving levels of water quality appropriate to those designated uses. However, although the NRCP prescribes the construction of sewage treatment plants and other capital investments to reduce water pollution, it does not provide a dedicated source of revenues to fund those investments. Greenstone and Hanna (2014) report that India's NRCP has not reduced water pollution concentrations in river segments covered by the plan. They attribute this failure to weak institutional support for the NRCP's goals and low public demand, because water pollution is less visible than air pollution.

In Vietnam, there is a comprehensive pollution control framework. The discharge of wastewater is regulated by the 2012 Water Resources Law, the Order on Exploiting and Protecting Irrigation Work, and a decree on drainage, sewage, and wastewater management, which asserts that "wastewater must be collected, treated, reused or transferred to functional units suitable for reuse or treatment up to environmental technical standards before being discharged into the environment" (Article 4). The system issues permits for discharge and fines for violations. Monitoring is limited, and the fines are deemed to be low and unevenly applied. For industrial wastewater, the tariff has a fixed and a variable component that depends in part on the level of pollution. This implies that the average tariff cost that a large polluter incurs is less than that faced by a small polluter, whereas both large and small polluters may face the same marginal tariff cost of pollution.[a]

a. This is a technical point. More precisely, the tariff structure is in the form $\tau = a + bE$ (in which E is emissions, a the fixed fee, and b the variable fee). The average burden on a polluter is τ/E. The average cost for the polluter is declining in E, while the marginal cost is b and a is the same rate faced by polluters, irrespective of emission levels.

When bureaucratic discretion combines with opportunities for rent seeking, the emphasis on command and control mandates may be counterproductive and less effective at controlling pollution than incentive-based approaches such as taxes. It has seldom been recognized that with command and control approaches there is a greater opportunity and incentive to evade regulations through rent seeking. This may explain why even in countries with a well-developed command and control architecture, enforcement of laws remains challenging and compliance with regulations is typically weak. Box 6.3 provides an explanation for why this occurs, with technical details relegated to the appendix.[2]

BOX 6.3: Instruments for Water Pollution Control—Command and Control versus Economic Incentives

Consider a pollution tax and a pollution standard that both generate the same level of pollution under perfect compliance with their respective policies. Suppose that there is bribery. Will there be a difference in pollution (that is, compliance) levels generated by these two instruments?

This most basic issue has not been explored in the literature. The question is of the relevance not just for water quality but also for a wider class of governance issues that require regulation in the context of asymmetric information and when enforcement capacity is imperfect. This is especially relevant in developing countries where pollution damage is growing and enforcement capacity is weak. A minimalist model to provide greater understanding and answers to this rudimentary, but critical, question is detailed in the appendix.[a]

The analysis finds that across a range of plausible circumstances that exist in low-capacity developing country contexts, regulation through command and control instruments results in greater levels of rent seeking, lower compliance levels, and hence higher levels of pollution. Conversely, when economic instruments such as pollution taxes are used to regulate compliance, there is less corruption and greater compliance. The intuition underlying this result is suggested in the following example: With a pollution tax, inframarginal rents (the profits for each unit produced) are lower than with the pollution standard. With lower rents, there is less ability to bribe for emissions to be underreported, which in turn increases compliance and results in better environmental outcomes.

a. www.worldbank.org/qualityunknown.

REACTIVE APPROACHES: END-OF-PIPE TREATMENT

The third and more prevalent approach to addressing pollution externalities is reactive and involves treating toxic discharges to render them less harmful to human health and the environment. This typically involves investments in treatment.

Somewhat paradoxically, the poorest countries, because of their weak administrative capacity, confront higher pollution control costs than do higher-capacity and typically more affluent economies. Prevention is often more cost-effective and safer than treatment of pollution. But it also calls for a significant level of administrative resources and an enforcement architecture. Whatever form of regulation is used—be it a standard, a technology mandate, or a tax—there is a need to monitor compliance with regulation and establish a system to adequately penalize violations. When this is not feasible, countries are left with the costlier option of treating pollution, and when treatment is funded through public finances, it entails an effective subsidy to the polluter. The implication is that the typical developing country today faces higher pollution control costs than richer countries, and some may inadvertently be subsidizing, instead of penalizing, polluters.[3] But as the next section indicates, with the rise of new technology, there are promising opportunities for real-time monitoring of certain pollutants and for enforcement procedures that eliminate rent seeking and other common evasion tactics.[4]

EVIDENCE OF POLICY EFFECTIVENESS

Despite the significant cost of pollution prevention and control, evidence of the effectiveness of different approaches remains sparse. Even the most essential information necessary to determine which policy options are most cost-effective is often missing. Assessments are impeded by a lack of data on the location of wastewater treatment plants (WWTPs) in most countries, the effectiveness of their performance over time, and the costs incurred.

When basic information on the costs of wastewater treatment is unavailable, determining cost-effective policy options becomes more a matter of informed conjecture than rigorous analysis in many circumstances. Accordingly, this study has attempted to partly fill this vital gap by gathering information about treatment costs from across the world to provide ballpark estimates that could assist in benchmarking costs and determining policy choices. The results for biological nutrient removal (BNR) are summarized in box 6.4 and indicate wide variation across regions and plant sizes, with capital costs accounting for most of the difference.

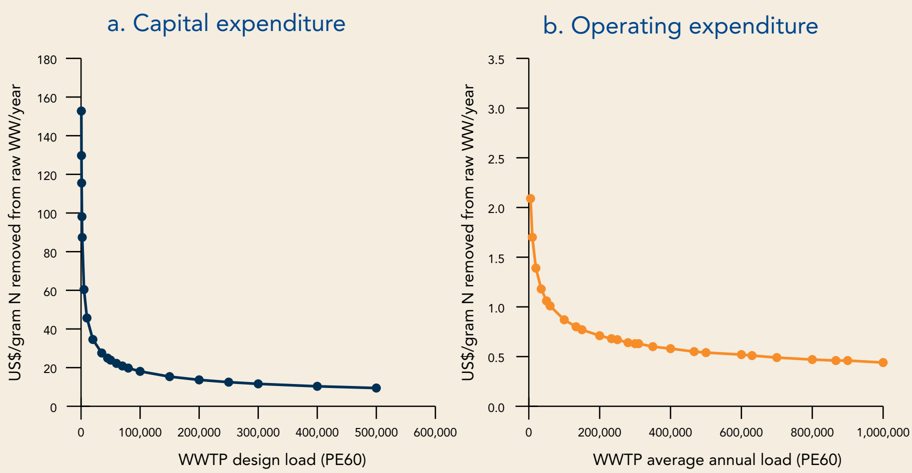
BOX 6.4: Elusive Price Tag of Wastewater Infrastructure

Measuring the cost of infrastructure is notoriously difficult. This is also true in the case of wastewater treatment plants (WWTPs). Somewhat surprisingly, to date, no database exists of these costs by country and region to allow project managers to compare costs across peers or determine whether treatment is cost-effective. To partly address this problem, this report has compiled a new database to compare the cost of biological nutrient removal (BNR) for different regions: Asia, Africa, Europe, and Latin America.[a]

Cost data were collected for a range of WWTP design capacities to reflect economies of scale. In addition, an exercise to estimate the cost of retrofitting was undertaken, because BNR technology is not widely used in some regions. Because WWTPs exhibit economies of scale, measurements are given in terms of population equivalents—a wastewater pollution load of 60 grams of the 5-day biological oxygen demand (BOD5) per person per day, termed *PE60*, which is the observed load in some European countries.[b] The cost curves are for an effluent quality within the safety thresholds.[c]

Figure B6.4.1, panel a, shows a range of costs that vary with the size of the WWTP. For capital expenditure (CAPEX), costs range from US$34.55 per gram of nitrogen removed from raw wastewater (denoted $N_{raw\ WW}$) for estimated removal for a design load of 20,000 PE60 (the average size in Europe) to US$18.06 per gram of $N_{raw\ WW}$ for an estimated removal for a design load of 100,000 PE60 (the average size in China).

FIGURE B6.4.1: Global Average Costs of Treating Wastewater



Source: Calculations based on data collected for this report (Poeppke and Buchauer 2019).
Note: N = nitrogen; PE60 = 5-day biological oxygen demand per person per day; WW = wastewater; WWTP = wastewater treatment plant.

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BOX 6.4: Elusive Price Tag of Wastewater Infrastructure *continued*

As can be expected the cost of the operating expenditure (OPEX) is lower. As seen in figure B6.4.1, panel b, OPEX cost ranges from US\$1.39 per gram of $N_{raw\ WW}$ for estimated removal for a design load of 20,000 PE60 to US\$0.87 per gram of $N_{raw\ WW}$ for an estimated removal for a design load of 100,000 PE60.[d] Looking at a design load of 100,000 PE60, the cost of retrofitting a BNR technology to an existing WWTP ranges from 21 percent of the CAPEX cost to 36 percent of the OPEX cost.

Those costs, as imperfect as they are given the paucity of data in many countries, show the important range of factors influencing the overall costs of treatment. Without such information, the overall cost of WWTP tends to be underestimated upfront, making other policy options appear less cost efficient. Better cost data on treatment infrastructure is urgently needed to enable policy makers to make better-informed choices.

a. Sources of data were published reports, papers, presentation, and in a few cases, information made available to the authors. For some regions, such as Africa, little cost data on BNR plants was available. In those cases, information on CAPEX and/ or OPEX from WWTPs with activated sludge and modern plastic media trickling filter technologies—but not designed for BNR—was collected. Based on data from other examples, the typical CAPEX and OPEX increases for WWTP upgrading to BNR technology were derived as percentages of the cost for WWTPs without BNR. This factor was then applied to come up estimates for WWTPs with BNR.
The most expensive CAPEX and OPEX component of BNR facilities is nitrification, that is, the conversion of ammonium nitrate-nitrogen (NH4-N) and organic nitrogen into nitrate-nitrogen (NO_3-N), because this requires large reactor volumes (CAPEX) and large amounts of oxygen (OPEX). The subsequent denitrification (conversion or elimination of part of that formed NO_3-N into gaseous nitrogen emitting into the open air) is less CAPEX and OPEX intensive (smaller reactors with no oxygen requirement), but it requires some pumping of the NO_3-N (produced during nitrification) back to those denitrification reactors, which are ideally located upstream of the nitrification reactors. This pumping is an operational task, and the ideal adjustment of it to daily load and flow fluctuations is what defines the effluent NO_3-N quality.

b. For both CAPEX and OPEX, a reference unit had to be chosen to reflect economies of scale. Among the two typical WWTP capacity references, daily design flow rate (in million liters per day) and design pollution load (in population equivalents), the latter was chosen, mainly because pollution load has a stronger impact on both CAPEX and OPEX than flow rate. When for a specific WWTP only capacity data for design flow was available, it was converted into the corresponding PE60 capacity of that WWTP. As is common practice, a slightly different approach was applied to the calculation of PE60-specific CAPEX versus OPEX cost values: Whereas in CAPEX assessments the PE60 design load was used, for OPEX assessments the average annual incoming PE60 load was used as a reference. A BOD5 load of 60 grams of BOD5 per PE per day is taken as a reference for this exercise; the authors acknowledge that BOD5 load per capita varies depending on the gross national income (Poeppke and Buchauer 2019).

c. A typical BNR effluent after 70 percent nitrogen removal has about 10 to 15 milligrams per liter (mg/L) of total nitrogen. From that total nitrogen, about 2 mg/L are made up of organic nitrogen, 1 to 5 mg/L are NH4-N, and the remainder is NO_3-N. The cost curves produced for this analysis can be interpreted such that WWTPs with such a cost are able to guarantee effluent quality with ≤10 mg/L of NO_3-N.

d. A wider cross-region variation is observed given the important contribution of labor and energy costs to this cost and the country-specific variation.

Given the significant cost of constructing and operating a WWTP, it is reasonable to ask whether the investments are effective in reducing pollution loads. This question remains largely unanswered, again because of a lack of information. To partially address this gap, this report investigates the cases of China and India, two countries that have heavily invested in treatment plants and published some data on key water quality parameters (box 6.5). The results are mixed at best.

BOX 6.5: Treating Wastewater—End-of-Pipe Solutions or Pipe Dreams?

Treatment plants are end-of-pipe technologies treating effluent from multiple sources before release into a river. Surprisingly, little rigorous evidence of their efficiency exists, particularly in developing countries. Looking at China and India, two countries that have invested heavily in treatment plants, this report used a difference-in-differences approach to causally capture impact on pollution and health outcomes, using the unidirectional nature of pollution along rivers.[a] When a treatment plant is built, changes in pollution resulting from the treatment plant will only be felt downstream, while upstream pollution levels remain unaffected, acting as a plausible control group.[b] Differences should also emerge when comparing before and after construction of a plant at a given location. The evidence from China and India is ambiguous.

While there are data limitations, in China it is possible that investments in treatment plants have lowered downstream pollution loads, as indicated by low levels of chemical oxygen demand farther downstream. This suggests that the investments can be effective, though it is not possible to determine whether this is always the case and whether these investments are cost-effective.

In India, the evidence so far points to limited effectiveness of wastewater collection and treatment in reducing pollution levels. Prior studies attribute these limited effects to weak institutional environments and low public demand for ambient water quality improvements (Greenstone and Hanna 2014). To provide a more precise identification of the institutional shortcomings, more data on ambient water quality and wastewater treatment plants (WWTPs) are collected to estimate the effect of treatment plants on pollution loads. The results show that the construction of treatment plants in India has no measurable effects on pollution levels. Furthermore, careful analysis of pollution levels for each of the years after the construction of a sewage treatment plant does not indicate delayed effects. Low sewage treatment capacity, low river flows, and poor

box continues next page

BOX 6.5: Treating Wastewater—End-of-Pipe Solutions or Pipe Dreams? *continued*

institutional oversight are likely explanations for this empirical result. Relative to the generation of household and industrial waste, most municipalities in India treat a small percentage of wastewater before it is released into waterways—only 31 percent of the generated sewage gets treated, with the remaining 69 percent released untreated into the environment (Kaur et al. 2012).[c] Additional benefits could be derived simply by using existing infrastructure at its full capacity.[d] Successive official reports by the government of India point to management issues and call for more efficient operation of these costly investments.[e] Unreliable energy supply, lack of skilled human resources, and irregular maintenance are some problems identified in these reports. This analysis covers the effects of WWTP construction on pollution levels for WWTPs built in India between 1984 and 2015, which precedes recent efforts to expand WWTP capacity.

a. The analysis compares measured pollution downstream of a treatment plant with pollution upstream of the plant before and after construction (a difference-in-differences approach).
b. A simple comparison of pollution levels before and after a treatment plant is built can lead to biased estimates, because many factors influence pollution levels beyond the construction of treatment plants, such as population changes, agricultural intensity, and industrialization. However, upstream-downstream approach considers pollution levels upstream of a treatment plant as a control group, providing a plausible counterfactual level of pollution to that observed at downstream monitoring stations.
c. An estimated 38,554 million liters per day of raw sewage are created in India, of which 11,786 million liters are treated, according to the Ministry of Environment and Forests (Kaur et al. 2012).
d. Anecdotal evidence suggests that many sewage treatment facilities are poorly managed and operate well below potential, sometimes because of high depreciation rates of physical capital and low ongoing investment after the initial construction of the facility.
e. Official reports by the government of India note that inspectors who visited 84 of the 234 known sewage treatment plants in 2007 found the performance of 46 (54.7 percent) to be "poor" or "very poor," with the performance of just 8 (9.5 percent) rated "good" (CPCB 2008). A more comprehensive investigation in 2013 tells a similar story (CPCB 2013). At that time, 152 sewage treatment plants were visited by investigators, and 58 (38.1 percent) were nonoperational or had unsatisfactory performance.

In China, there is some suggestive evidence, in some statistical specifications, that investments in WWTPs have lowered downstream pollution loads of key pollutants. However, in India, the evidence shows limited impact of investments in WWTPs. In a widely cited paper, Greenstone and Hanna (2014) found that investments in WWTPs appear to have no measurable effect on pollution loads in India. A replication of this exercise using similar but more recent data conducted for this report confirms this result. This may be a consequence of the way that WWTPs are managed as suggested in official documents of the government of India, or it may be because treatment capacity is simply insufficient to reduce the amount of wastewater generated, or it could be a consequence of lack of flows necessary to dilute treated wastewater.

While there is limited evidence of the costs and impacts of wastewater treatment, there is even less empirical evidence of the effectiveness of other policy instruments and programs for preventing pollution (Keiser and Shapiro 2018; Olmstead and Zheng 2019). Moreover, many evaluations that have been undertaken are partial and may be misleading, because they often ignore the full range of benefits that treatment and prevention may confer (Keiser, Kling, and Shapiro 2019).[5]

For nonpoint source pollution arising from land use activities, policies such as payments for hydrological or environmental services are often recommended to reward and incentivize preventative actions. Anecdotal evidence is suggestive of success. An iconic example of such a scheme is in the Catskill Mountains, which serve as a watershed for New York City. New York City pays farmers to adopt environmentally friendly farming techniques, and the city spends less money on water treatment—a win-win situation. Another example comes from China, where the government in Beijing began paying farmers upstream of the Miyun reservoir (its only surface water reservoir) to convert land from rice cultivation to dryland crops, with the dual goals of increasing water yield in the catchment and reducing nutrient flows into the reservoir.[6] A recent assessment of this program suggests that it has been successful, with an estimated benefit-cost ratio of 1.5 and net benefits flowing to both upstream service providers and downstream payees (Zheng et al. 2013). Many smaller-scale systems have been established in Latin America. For example, in Colombia's Chaina watershed in the eastern Andes, downstream water users pay upland farmers for changes in land management practices that reduce soil compaction and erosion.

A concern that besets studies of payment for environmental service schemes is determining the additionality of the scheme—an unobservable counterfactual state that defines what would have happened had the policy not been implemented. There is always a statistical counterfactual that can produce the desired result, suggesting that evidence of success is not conclusive.

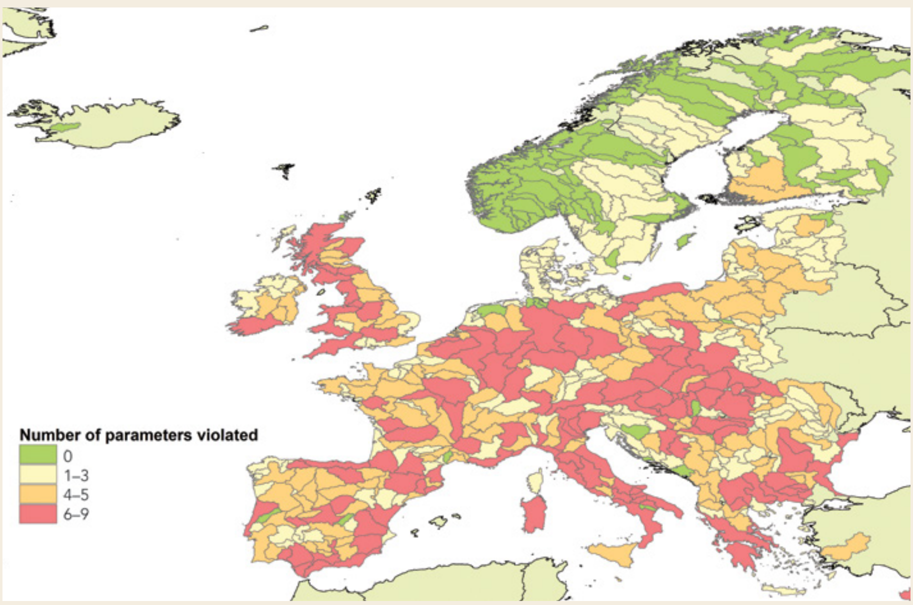
Whereas there is limited evidence of which policy works best, there are data, in most developed and some developing countries, for compliance levels with existing laws and regulations. The evidence that exists suggests that violations of pollution laws and mandates are common in both developing and developed countries. For instance, in Europe, with its comprehensive and vigorous approach to water quality problems, nearly every country violated surface water standards for important parameters between 2000 and 2012 (box 6.6).

There is also evidence from the United States, especially following the dramatic events in Flint, Michigan. These assessments suggest that violations of drinking water standards are more common in systems serving larger and poorer communities (McDonald and Jones 2018). These happen to be locations that confront a perfect storm of aging infrastructure, polluted water sources, and binding budget constraints (Allaire, Wu, and Lall 2018). This

BOX 6.6: Surface Water Quality in the European Union

An analysis of the water quality of Europe's rivers using the Waterbase[a] database of the European Environment Agency and focusing on nine key parameters (arsenic, biological oxygen demand [BOD], dissolved oxygen, lead, mercury, nitrate, nitrite, pH, and total ammonium) suggests that even in Europe, violations of international standards are common.[b] More than 20 percent of 538 subbasins[c] on the continent with monitoring stations violated water quality standards in at least six of the nine parameters tracked between 2000 and 2012 (map B6.6.1). Worse, nearly every country has had at least one violation of these nine parameters between 2000 and 2012 (Iceland, Malta, and Norway being the only exceptions), and some countries have more than 30 percent of their observations of these nine parameters violating standards over this period.

Map B6.6.1: Number of Water Quality Parameters Violated, by Water Basin, 2000–12



Source: Calculations based on data from European Environment Agency Waterbase for rivers.

Depending on their status as preaccession, candidate member, or member state, countries in this region have paid and continue to pay close attention to improving water supply and sanitation services to comply with or make progress toward compliance with the Drinking Water Directive and the Urban Waste Water Directive, two critical

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BOX 6.6: Surface Water Quality in the European Union *continued*

directives under the European Union Water Framework Directive. This has meant that investments have focused on urban areas and large agglomerations to improve drinking water systems and rehabilitate and build wastewater collection and treatment infrastructure. Still, this analysis highlights the difficulty of tackling water quality even in a wealthier region of the world known for its advanced regulatory system.

a. Waterbase is the generic name given to the European Environment Agency's databases on the status and quality of Europe's rivers, lakes, groundwater bodies, and transitional, coastal, and marine waters; on the quantity of Europe's water resources; and on emissions to surface waters from point and diffuse sources of pollution. The data set includes measurements for 772 dangerous substances.
b. Standards are from the World Health Organization (total ammonium < 1.5 milligrams per liter [mg/L] and BOD < 5 mg/L) and the U.S. Environmental Protection AGency (lead < 15 micrograms [μg]/L, mercury < 2 μg/L, arsenic < 10 μg/L, nitrates < 10 mg/L, and nitrites < 1 mg/L); pH is broadly defined as being acceptable if in the range 5–9.
c. Subbasin boundaries were obtained from the World Wildlife Fund's HydroSHEDS database (https://hydrosheds.org/), and Pfafstetter level 6 was used.

suggests that understanding the political economy of regulation is critical for the design of environmentally effective programs that are economically efficient and cost-effective.[7]

THE PREREQUISITES FOR SUCCESS

Efficient and effective pollution control requires that countries have at their disposal the full range of available policy and investment options and that they select those that are most cost-effective. This section describes how those options can be implemented and made more efficient. Ultimately, responses require a mix of approaches, blended to reflect the specificities of regulatory feasibility and the water quality challenges at hand:

- Incentives and policies for prevention are often more desirable, safer, and more cost-effective than treatment, but they call for effective enforcement architecture.
- Investments in treatment are still critical, because it is usually impossible or prohibitively expensive to mitigate all pollution at the source.
- Information has high economic value when there is uncertainty. Policies that inform citizens of the risks and possible consequences allow consumers to more effectively take avoidance actions that align with their risk preferences.

INCENTIVIZING PREVENTION

Incentives are necessary to prevent pollution at source. Meeting environmental standards is expensive and may require investments in cleaner technologies, changes in production techniques, or more costly ways of disposing waste. Where the costs of compliance exceed the anticipated consequences of noncompliance, companies will simply view the risk of incurring a penalty as a cost of doing business. Understanding the underlining behaviors of all stakeholders is also important to design effective prevention policies and interventions (box 6.7) and may make policies more effective.

For prevention to be effective, emissions need to be monitored for compliance levels. There also needs to an effective system of enforcement to deter violations. Recognizing that regulations create incentives for evasion and rent seeking, a system that is effective will require a measuring and monitoring component that is reliable and tamperproof and an enforcement component that is corruption proof and provides incentives for compliance.

BOX 6.7: Nudging the Way to Good Water Quality

There could be opportunities to alter behavior and change damaging consumption and production patterns through education, contextual cues, and social norms that signal consent or disapproval. These tools based of behavioral nudges do not displace existing policy approaches that target incentives; rather, they complement and enhance them. Some of these approaches may cost little to implement, because they depend on nuances in messaging and policy design, and others may entail longer periods of engagement, especially when changes in attitudes and values are involved.

Behavioral tools have been used to promote water conservation. For instance, in Costa Rica (Datta et al. 2015), a successful intervention focused on benchmarking water consumption levels between peers (Allcott 2011; Ferraro and Price 2013).[a] The outcomes of other interventions have been more varied (Byrne, La Nauze, and Martin 2018),[b] suggesting the need for further research.

There appears to be potential to use such interventions to alter consumer behavior in the water quality context too, such as with the use and disposal of plastics or pharmaceuticals and perhaps even the behavior of commercial enterprises. The interventions are likely to be more effective when combined with appropriate incentives, rather than when used in isolation.

box continues next page

BOX 6.7: Nudging the Way to Good Water Quality *continued*

Richard Thaler's 2017 Nobel Prize and the creation of special units like the United Kingdom's Behavioral Insights Team are perhaps indicative of the potential of such approaches (Thaler 2018). The overarching conclusion is that these new tools do not displace existing policy approaches based on incentives; rather, they complement and boost them.

a. The concept goes back to the Kahneman and Tversky (1979) conceptual breakthrough with the prospect theory. As noted by Thaler himself in his Nobel Prize essay: "whereas their earlier research stream was about judgments, prospect theory was about decisions, particularly decisions under uncertainty. The theory is now nearly four decades old and remains the most important theoretical contribution to behavioral economics. It broke new ground in two ways. First, it offered a simple theory that could explain a bunch of empirical anomalies … , and second, it illustrated by example that economics needs two types of theories: normative and descriptive. By normative here I mean a theory of what is considered a rational choice (rather than a statement about morality). In contrast, a descriptive theory just predicts what people will do in various circumstances. The basic flaw in neoclassical economic theory is that it uses one theory for both tasks, namely a theory of optimization" (Thaler 2018).

b. Looking at retail electricity, Byrne, La Nauze, and Martin (2018) show that high- and low-energy users systematically underestimate and overestimate their relative energy use. Responses to personalized feedback on usage levels, resulted in asymmetric responses. Households that overestimate their relative use and low users both responded by consuming more. These boomerang effects provide evidence that peer-comparison information programs, even those coupled with normative comparisons, are not guaranteed to lead to increases in prosocial behavior.

Measurement

Measurement of water quality is a critical first step to preventing pollution. Few developing countries adequately monitor water quality, even when regulations are in place to limit pollution. It is impossible to adequately regulate pollution unless compliance levels are monitored. A key challenge is that systems in place for assuring compliance create incentives to manipulate data to shield polluters. This is a classic economic problem of asymmetric information commonly encountered in tax administration and environmental problems, where the polluter has better information and the inspector reporting compliance levels has discretion, allowing the possibility of collusion in reporting emission levels.

Advances in technology can provide ways of circumventing this problem and have made measurement more feasible and reliable. Recent trials have demonstrated that multilayered monitoring systems involving several parties can improve the reliability of data collected (box 6.8). These in turn can be complemented with remote sensing and machine learning to provide an additional and independent layer of verification. Blockchain technologies, though still in the experimental stages of use in the water sector, can offer

BOX 6.8: Blockchain Meets Water Quality Monitoring

Blockchain has been in the news recently with the popularization of cryptocurrencies such as Bitcoin or Ethereum. However, blockchain technology's possibilities go far beyond what these cryptocurrencies offer. Blockchain at its core is nothing more than a ledger for accounting or storing information. What makes it so revolutionary is that it is also immutable (its data cannot be tampered with), decentralized (there is no central authority), and transparent (public blockchains are viewable to all).

These properties solve many of the credibility problems associated with water quality monitoring in countries with high rent-seeking behavior. Water quality data stored on a blockchain are wholly transparent and tamper proof. The ledger can then be coupled with a third-party or multiparty monitoring system or with automatic monitors (for parameters that do not require a laboratory) to ensure that the data generation and dissemination chain is sealed off from manipulation. Systems like this are already in place in Canada,[a] on the Volga River in the Russian Federation (Libelium World 2018), and elsewhere.

Smart contracts, which are built on top of blockchains, offer another game-changing opportunity for the water quality sector. Smart contracts are contracts written in code that include rules, conditions, expiry dates, and other necessary information that are embedded in a blockchain and automatically execute when the conditions are met. When coupled with automatic monitoring of water quality, they can offer a fully automated solution for imposing tariffs or penalties on companies found discharging pollutants in excess of what is allowed. Most critically, they cut out the need for human monitoring, and with that, the possibility for corruption or rent-seeking behavior.

a. Example of use of blockchain technology, supported by the RBC Foundation, to provide a distributed ledger on the Ethereum network and traceability that allows users to see how data changes over time, improving the security and authenticity of data. https://atlanticdatastream.ca/#/news/W5-zWiUAACUA3Hjy.

a promising added layer of verification and transparency at low cost and with increasing reliability with the inclusion of newly collected data. The use of machine learning, illustrated in this report, demonstrates that such approaches can produce predictions that can be used to complement onsite estimates and identify outliers and potential violators. Furthermore, these types of approaches will continue to improve as more data become available.

Experience suggests that third-party monitoring can offer a useful complement to conventional approaches. For instance, Duflo et al. (2013) provide evidence that third-party monitoring reduces corruption and improves the quality of data collection. Citizen science can also increase the scope of water quality data collection by governments that have limited resources. In the United States, the U.S. Environmental Protection Agency (EPA) supports multiple volunteer water quality monitoring programs throughout the country, including through the Equipment Loan Program, to assist citizen science water monitoring programs (Freitag et al. 2016).[8] Moreover, citizen science and other crowdsourcing approaches may provide opportunities to educate, engage, and empower the public (World Bank 2016a) and encourage environmental compliance (Grant and Grooms 2017). In developing countries, with the increasing availability of mobile phones and Internet access, citizen scientists could make a significant contribution to future water quality data collection, although recent evidence from a World Bank–supported project in Punjab suggests that there are limits to this approach (World Bank 2016a, 2016b).[9]

Compliance and Control

Measurement needs to be accompanied by sanctions and penalties to ensure compliance. In developing country contexts where fines, when levied, are low, companies view them as a cost of doing business. The process of enforcing penalties is often complex, involves significant transaction costs, and remains vulnerable to the risks of rent seeking.

New technologies can be harnessed to improve enforcement. With more systematic and verifiable data collection comes options to enforce standards and regulations. For instance, smart contracts implemented on blockchains could be used to automatically enforce payment for polluters. Smart contracts are written in code that include rules, conditions, expiry dates, and other necessary information embedded in a blockchain, and they automatically execute when the conditions are met. If there is a violation, a smart contract would automatically trigger the payment of a fine. This would provide a corruption-proof, highly transparent, and arguably even more cost-effective way of regulating pollution, especially when corruption risks are high (box 6.8).

INVESTMENTS

Infrastructure will continue to play an important role in treating what cannot be prevented. The costs of treating water are significant. For the given parameters described in box 6.4, a plant with a capacity of 20,000 5-day biological oxygen demand per person per day (PE60) has levelized costs varying from around US\$20 to US\$35 per gram of $N_{raw\ WW}$ up to around US\$70 per gram of $N_{raw\ WW}$. Reflecting scale economies, a larger plant has lower costs. For instance, with a capacity of 100,000 PE60 costs vary from around US\$12 to US\$22 per gram of $N_{raw\ WW}$ up to around US\$38 per gram of $N_{raw\ WW}$.[10] With a shortage of public funds, investments in water treatment need to be made more attractive for the private sector by lowering risks and assuring a fair return to investors. One such model is the hybrid annuity scheme pioneered by the government of India, under which a proportion of the capital cost is paid during the construction phase, with the remainder paid over the life of the project as annuities that are linked to performance.

INFORMATION

Information disclosure is an especially valuable tool for consumers to make choices that align with their preferences and appetite for risk. When there is uncertainty, information is especially valuable for guiding behavior. As the analysis in chapter 2 suggests, there is considerable uncertainty about the safe thresholds of key water pollutants that are pervasive across the world. In such circumstances, the provision of clear and understandable guidelines about the existing evidence and uncertainties involved would equip consumers with the ability to make better choices.

Evidence suggests that information disclosed to households in developing countries facilitates better household decisions. For example, field experiments in Bangladesh and India found significant responses by households to information about arsenic levels in drinking water wells (Barnwal et al. 2017; Madajewicz et al. 2007). Knowledge that a well had an unsafe arsenic concentration increased the probability that a household would switch to another well within one year (Madajewicz et al. 2007). Nevertheless, individual remedies are often less efficient than large public works and have the potential to cause unexpected effects (box 6.9).

One of the most powerful outcomes of information disclosure is how it can inspire citizen engagement and social movements, as was seen in the wake of the Cuyahoga River fire in northern Ohio. Improving water quality requires not just knowledge and resources but above all political will. When governments fail to control pollution, they are allowing individuals or companies to impose high costs on their citizens while reaping private gains. There are many reasons this so easily and frequently happens, but perhaps chief among them is information asymmetry. Citizens cannot demand political change if they are uninformed or unaware of the situation. Encouraging and enabling this information is fundamental to the social contract that exists between the governed and the governors and is critical to getting this wicked problem under control.

THE WAY FORWARD

Given the complexity of the problem, there is no foolproof, one-size-fits-all prescription for solving a country's water quality problems. Instead, policy makers must address the problem with a multitude of tools. Depending

BOX 6.9: Reverse Osmosis Boom in India

In recent years, small-scale domestic reverse osmosis water treatment filters have increased in popularity in India. This is largely in response to the deterioration of water quality in many parts of the country. Although there is no nationwide estimate of the use of reverse osmosis in India, there is growing evidence that adoption of this technology has grown exponentially in recent years. For instance, market analysis shows reverse osmosis adoption rates of 15 percent in Greater Mumbai and 25 percent in Delhi, along with greater rates (77 percent) among higher-income groups (AnalyZ Research Solutions 2012; Ghosh, Kansal, and Aghi 2016).

Although the use of reverse osmosis technology provides a response to poor water quality, it comes with heavy costs. First, it may be too expensive for universal adoption. Despite a fall in costs in recent years, many households in India, particularly the poorest, who are disproportionately at risk from poor water quality, are least likely to be able to afford these filters. Furthermore, because reverse osmosis requires high electricity usage, this technology can be a drain on limited resources, especially in places where power shortages are endemic. Third, the process of reverse osmosis is unlikely to be sustainable at scale. For instance, purifiers discard as much as 30 to 80 percent of water. To add to this, the waste that is generated is substantial and far dirtier than the original water. Astonishingly, reverse osmosis requires up to 100 liters per household per day to treat 5 liters of drinking water. If all households within the top two socioeconomic groups were to adopt this technology, this would amount to 82.2 megaliters per day in the city of Delhi alone and 2,340 megaliters per day across all major urban areas of India (O'Connor 2016). In a country already facing water scarcity, reverse osmosis cannot be the panacea to poor water quality. It exemplifies the wicked nature of water quality, where one solution leads to a litany of new problems.

on the capacity of the country, policies should work their way up a ladder of interventions that begin at relatively low effectiveness but are easily implemented and then increase in complexity and impact. Figure 6.2 displays such an intervention ladder as a guide for policy makers and institutions.

The ladder contains six policy arenas, and each arena has three stages. A country need not move along each of the arenas in synchrony. Most countries will begin in differing stages depending on their relative capacity, and costs of moving along the ladder will differ. Decisions on which policies to advance will therefore be country specific and should be based on risk, feasibility, and cost-effectiveness.

FIGURE 6.2: Ladder of Policy Interventions

	Passive		Proactive		Reactive	
	Information		**Prevention**		**Investments**	
	Trans-parency	**Monitoring systems**	**Enforce-ment**	**Legislative framework**	**Financing**	**Treatment**
STAGE ONE	Publish data online and in regional/global databases, as well as in schools and health centers	Establish water quality monitoring for major water sources (surface and groundwater)	Codified laws and regulations in place that incentivize the reduction of point and nonpoint source water pollution with clear jurisdictions for enforcement and sufficient levels of devoted resources		Treatment is publicly financed	100% of drinking water is treated (SDG 6.1.1)
STAGE TWO	Overlapping systems with remote sensing or alternative monitoring infrastructure	Systematically monitor water quality in all sources of surface and groundwater	Smart contracts and automatic monitoring	Command and control structure	Incentives are put in place to attract private sector investors	100% of wastewater is safely managed (SDG 6.2.1)
STAGE THREE	Third-party or disaggregated publishing and verification system such as blockchain	Remote sensing or overlapping systems and early warning	Costs of water pollution are fully internalized by polluters	Economic incentives (taxes, permits, payment for services schemes, etc.)	Treatment is financed through a blend of private sector financing and tariffs levied on polluters	Tertiary treatment of drinking and wastewater for denitrification

INFORMATION

Monitoring Systems

Monitoring water quality is fundamental to controlling it. Establishing a network or system of water quality monitoring is therefore the first priority for any country that is serious about tackling water quality issues. With constrained resources, a country should prioritize the monitoring of major water sources. Once a system is in place, it should be expanded to track all major surface and groundwater sources in the country. Finally, more advanced overlapping systems can be deployed, such as remote sensing and machine learning to add a layer of verification.

Transparency

Although water quality data are critical for regulators, their value increases exponentially when they become available to the public. This allows individuals and businesses to make smarter and more informed decisions on matters that effect their health, livelihoods, and productivity. Relative to the expenses of monitoring water quality, publishing the data online is a low-cost complement that pays tremendous social dividends.

There is more to transparency than simply publishing data. Unless the data are open sourced or verified in some way, their accuracy can always be questioned. Therefore, implementing monitoring systems that overlap and verify one another will increase trust in data and identify errors. Finally, in countries where rent seeking is endemic, new technologies such as blockchain, coupled with automatic monitoring systems such as those used in China, can offer fully transparent and reliable data on water quality.

PREVENTION

Legislative Framework

Constructing a clear and comprehensive set of laws around water pollution is critical to protecting water resources. Once the system of regulation is in place, regulators must choose the type of regulation. Command and control regulations are the simplest to implement, but they are often also the least efficient and enable rent-seeking behavior. Economic incentive schemes such as pollutant taxes, tradable permit schemes, or in the case of nonpoint source pollution, payment for environmental or watershed service schemes have the best outcomes but are the hardest to implement.

Enforcement

Enforcement of water quality standards also begins with constructing a proper legislative framework. Countries with particularly low capacities and high risks for rent-seeking behavior can circumvent these problems by establishing automatic monitoring systems. Relatively new technologies such as blockchain and smart contracts can automate enforcement. Ensuring that the costs of treatment and prevention of water pollution are fully internalized by the polluters through taxes, fines, or other means is important for both sustainability of the regulatory system and justice for citizens.

INVESTMENTS

Treatment

Treatment of polluted water is not a panacea to the water quality problem, but it is a necessary component. Treating both drinking water and wastewater is critical for a country's health, economy, and environment. The ladder shown in figure 6.2 gives priority to treating drinking water because of its proximity to health impacts. Nevertheless, treatment of drinking water and wastewater occur in tandem, and decisions on which to prioritize should be based on estimated impacts and economic efficiency. Finally, as shown in chapter 2, nitrogen in drinking water is a critically underappreciated problem. Other than reverse osmosis, no home remedy exists for denitrifying water. Thus, denitrifying water at treatment plants is crucial. Nitrogen removal is also expensive, which makes this a higher hurdle than traditional drinking water treatment.

Financing

Innovation in the water treatment sector has been limited compared with other sectors. This is largely because most treatment plants are publicly financed. With little incentive to invest in research and development, technology stagnates. Countries can achieve a win-win outcome by putting incentives in place that attract private sector investors, incentivizing innovation, and generating additional financing for the sector, which frees public money for different priorities. A range of guarantees and risk reduction schemes are available to favorably tilt the risk-reward ratio, making private investments in the sector more attractive. Finally, as discussed in the section on enforcement, for reasons of fairness, investment financing should also come from polluters. A blend between private and tariff financing, or systems that have polluters paying private sector companies directly to perform treatment, may be warranted.

CONCLUSIONS

Although water quality is a wicked problem, increasingly complex and with uncertainty surrounding its impacts, instruments exist to tackle it. They require political commitment at the highest level, reflecting the size of the challenge. The good news is that modern technology can do much to resolve the problems that have impeded progress in the past and to make pollution prevention a more effective, cost-efficient, and realistic outcome.

NOTES

1. Some countries are beginning to experiment with such approaches. For example, the Pay for Permit pilot program in the Lake Tai Basin in China, launched in 2009, charges companies for every unit of pollution, a classic environmental tax (He, Wang, and Zhang 2018).
2. http://worldbank.org/qualityunknown.
3. This is a standard optimizing problem. In most cases, the cost-minimizing strategy will involve a combination of prevention and treatment. In particular, the optimal mix must equate the marginal cost of each option to minimize total costs. Thus, if an option such as prevention is denied, then total costs will be higher than if that option were available and less cost-effective as treatment over at least some feasible and relevant range.
4. An example is the China national specially monitored firms (NSMF) pilot program, established in 2007. This program identified specific firms that were major emitters and provided centralized oversight. NSMFs are required to install automatic monitoring systems and transmit emissions information in real time to the central government. Using a regression discontinuity design, He, Wang, and Zhang (2018) find that the additional central supervision of local authorities in the NSMF program reduces industrial chemical oxygen demand emissions by 26.8 percent in the first year, with continuing reductions in later years. One can do even better now with blockchain techniques, as noted in this chapter. He, Wang, and Zhang (2019) also show that the regulation effect is stronger when improved technology makes it harder to manipulate water readings, suggesting that local politicians have incentives to misreport environmental data in the absence of a precise monitoring practice.
5. Keiser and Shapiro (2018) found that nonpoint source pollution was largely ignored by the Clean Water Act, contrasting the Clean Air Act, which covers all major polluting sectors.
6. Beijing's Guangting reservoir closed in 1997 because of heavy pollution from wastewater discharges, fertilizers, and pesticides (Zheng et al. 2013).
7. For instance, in China, He, Wang, and Zhang (2019) calculate the economic costs of tightening water pollution regulations at a 10 percent reduction in chemical oxygen demand emissions as leading to a 2.49 percent decrease in total factor productivity.
8. We know of no empirical papers that use water quality data collected through citizen science initiatives. However, Kolstoe and Cameron (2017) use the eBird data set (a citizen science project from Cornell University) to evaluate willingness to pay for preservation of bird species (Olmstead and Zheng 2019).
9. For instance, a World Bank–supported pilot with the government of Punjab, India, developed a water quality mobile application (m-App) to be used for communication and data collection by field staff from the state's department of drinking water supply and sanitation. The m-App guided the users through the screening process by first prompting users to input basic information (such as water source and household member present) and then leading them through the steps for screening conductivity, pH, nitrate, total iron, free chlorine, and coliform. For screening, each analyte requires additional materials and/or equipment, including probes (conductivity), test strips (pH, nitrate, and total iron), and the Akvo Caddisfly chamber (free chlorine). Except for coliform, results were returned to the user within a minute and written to the Akvo Flow database. For the coliform test, the water sample was placed in a sampling container containing reagents, rested for 24 hours, and then read by the user and manually entered into the water quality m-App. At US$31.98 per screening, the screening routine is difficult to scale. The costs per sample would decrease substantially if the number of analytes screened is reduced (six in the given pilot; World Bank 2016a and 2016b).
10. These estimates are based on an assessment conducted for this study.

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Water quantity—too much in the case of floods, or too little in the case of droughts—grabs public attention and the media spotlight. Water quality—being predominantly invisible and hard to detect—goes largely unnoticed. *Quality Unknown: The Invisible Water Crisis* presents new evidence and new data that call urgent attention to the hidden dangers lying beneath water's surface. It shows how poor water quality stalls economic progress, stymies human potential, and reduces food production.

Quality Unknown examines the effects of water quality on economic growth and finds that upstream pollution lowers growth in downstream regions. It reveals that some of the most ubiquitous contaminants in water, such as nitrates and salt, have impacts that are larger, deeper, and wider than has been acknowledged. And it traces the damage to crop yields and the stark implications for food security in affected regions.

An important step toward tackling the world's water quality challenge is recognizing its scale. The world needs reliable, accurate, and comprehensive information so that policy makers can have new insights, decision making can be evidence based, and citizens can call for action. The report calls for a paradigm shift that emphasizes safer, and often more cost-effective remedies that prevent pollution by combining smarter policies with newer technologies. A key message of *Quality Unknown* is that such solutions exist and change is possible.

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