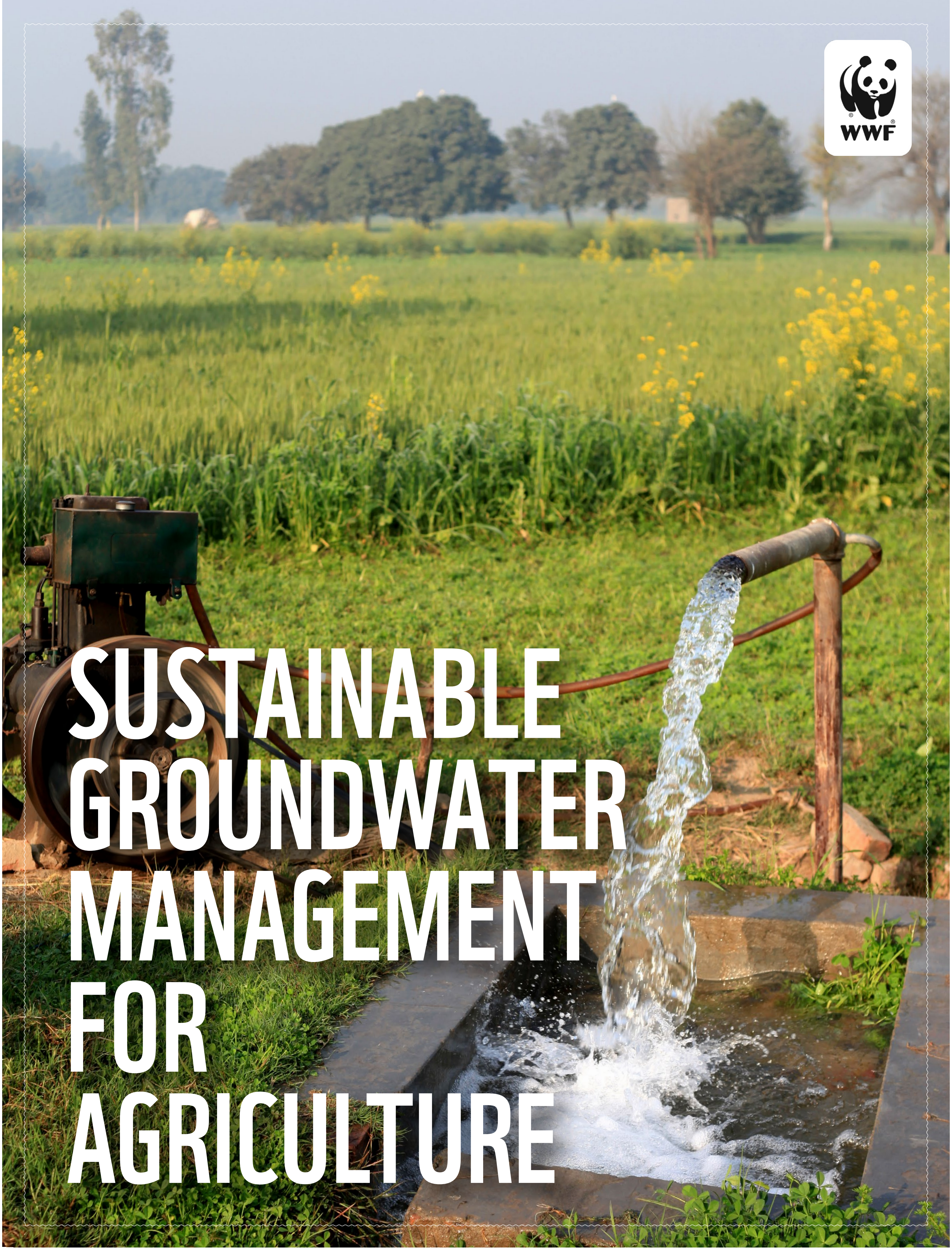

SUSTAINABLE GROUNDWATER MANAGEMENT FOR AGRICULTURE

AUTHORS

BRIAN RICHTER
WWF Senior Freshwater Fellow
President | Sustainable Waters

MELISSA D. HO
Senior Vice President
Freshwater and Food | WWF-US

SUSTAINABLE GROUNDWATER MANAGEMENT FOR AGRICULTURE

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FOREWORD

Today, 7.3 billion people consume 1.6 times what the earth's natural resources can supply. By 2050, the world's population will reach 9 billion and a business-as-usual approach, without significant changes to how we produce, consume and dispose of food, will see demand for food double. That will lead to increased pressure on the natural resources on which food production relies - including one that most food requires: freshwater.

In contrast to the immense importance of freshwater, it is a finite resource. Freshwater supplies make up only 2.5% of all the water on our planet, and two-thirds of that freshwater is frozen in glaciers and ice caps. That means that less than 1% of all water on our planet is accessible for our use and for supporting freshwater ecosystems. And most of that accessible freshwater is found underground.

Groundwater, which makes up the majority of available freshwater for all human uses, is increasingly threatened by overuse. Sustainably managing groundwater poses considerable challenges, but we must find solutions and protect this resource, which is essential to the future of drinking water supplies, food production, and ecosystem health. This report is a primer about these challenges and potential solutions to sustainably manage our planet's groundwater resources for the shared benefit of people and nature.

By defining the trends and drivers that have pushed groundwater use beyond sustainable levels—especially for agricultural production—and developing a shared understanding of the types of solutions that are possible and currently exist, we can begin to craft a vision for the future of sustainable groundwater management. We can shift our consumptive habit of freshwater and bring our use of groundwater back into alignment with long-term sustainability.

FOREWORD BY

JOÃO CAMPARI
PRACTICE LEADER, FOOD
WWF INTERNATIONAL

STUART ORR
PRACTICE LEADER, FRESHWATER
WWF INTERNATIONAL

SUSTAINABLE GROUNDWATER MANAGEMENT FOR AGRICULTURE

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GLOSSARY

Aquifer—Saturated water-bearing rock, sand, or gravel; the holding space for groundwater.

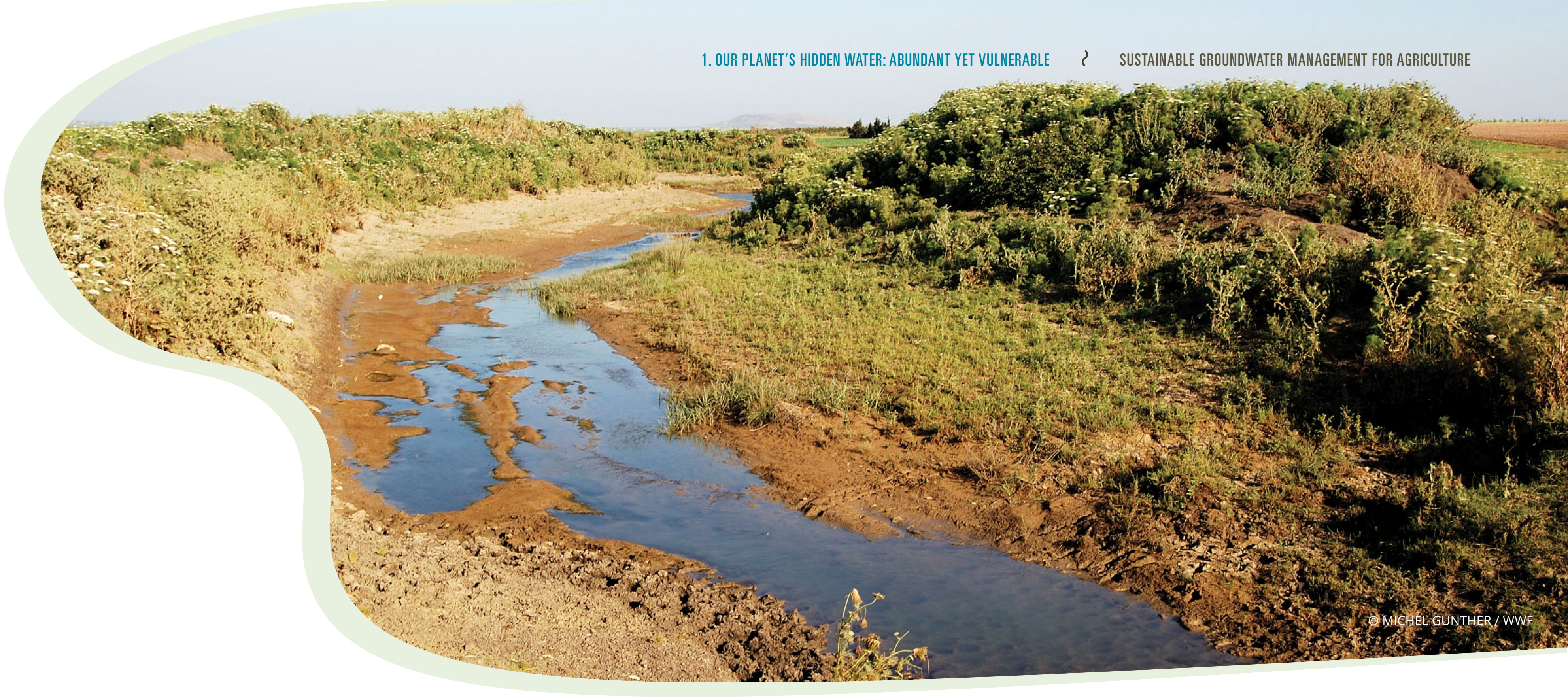
Groundwater depletion—The action of pulling groundwater out of an aquifer faster than the water resources are being replenished; also known as "over-pumping," "overdraft," or simply "depletion."

Recharge—Infiltration or injection of water into an aquifer from rain, snow melt, river flow, or other sources of surface water; this process can be natural or managed by people. Also known as "replenishment."

A VISION FOR GROUNDWATER SUSTAINABILITY

We envision a future where groundwater is valued and managed as a renewable resource to support human livelihoods, food production, and well-being as well as the integrity of ecological systems. Our use of groundwater in the short term must not jeopardize its future availability for human use, nor its continued sustenance of freshwater ecosystems—including aquatic, riparian, wetland, estuarine, and subterranean habitats and the species they support. We need to monitor and manage our groundwater use such that aquifer levels and exchanges between groundwater and surface waters remain dynamically stable and resilient, especially in the face of climate change.[1,2]

1 OUR PLANET'S HIDDEN WATER: ABUNDANT YET VULNERABLE



The vast majority of the water on Earth is ocean water, too salty for our direct use (Figure 1). *Freshwater supplies* make up only 2.5% of all the water on our planet, and two-thirds of that freshwater is frozen in glaciers and ice caps. That means that less than 1% of all water on our planet is accessible for our use and for supporting freshwater ecosystems. And most of that accessible freshwater is found underground.

Vast stores of groundwater exist beneath the surface of our planet, pooled in *aquifers* comprised of saturated sand, gravel, or porous rock layers (Figure 2). The volume of this groundwater is enormous—30 times greater than all accessible water on the surface of our globe.[3] If all the planet's groundwater were to be pumped to the surface and spilled evenly onto the land, it would drown us under 180 meters of water![4]

While groundwater aquifers are vast both in their global distribution and in their volume, most are either too deep for affordable access or highly vulnerable to overexploitation. More than 80% of all groundwater located within one kilometer of the land surface is "fossil water"—water that is more than 12,000 years old (pre-Holocene).[5] This fossil water, which is generally deeper than 250 meters,[6] percolated underground or was a river or lake that was buried by sediments long ago. Because fossil water aquifers lie so deep underground, they are not replenished by percolating rainfall or river seepage, so pumping fossil water will almost always deplete the aquifer. Countries using the greatest volumes of fossil water include India, Pakistan, the United States, Iran, China, Mexico, and Saudi Arabia.

Non-fossil groundwater (approximately 20% of global groundwater reserves) is much younger, having accumulated in shallower aquifers since about 1950.[7] Most groundwater wells around the world extract this "modern" water simply because it is more accessible and much less expensive to pump, given high electricity costs.

We have been extracting and using groundwater for at least 9,000 years.[8] Our initial access to groundwater was enabled by digging shallow wells by hand—most just a few meters deep—but today we use powerful drills that can penetrate aquifers that are tens to hundreds of meters deep[9,10] and industrial pumps to lift groundwater to the land surface for our use.

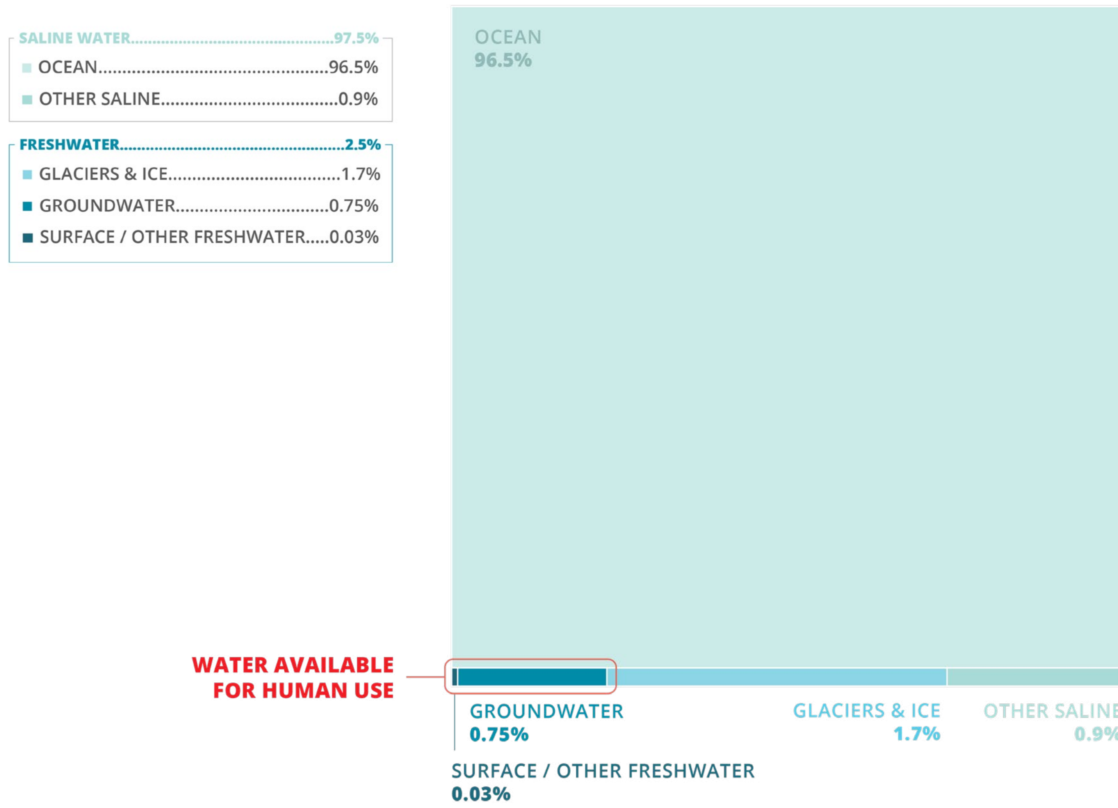
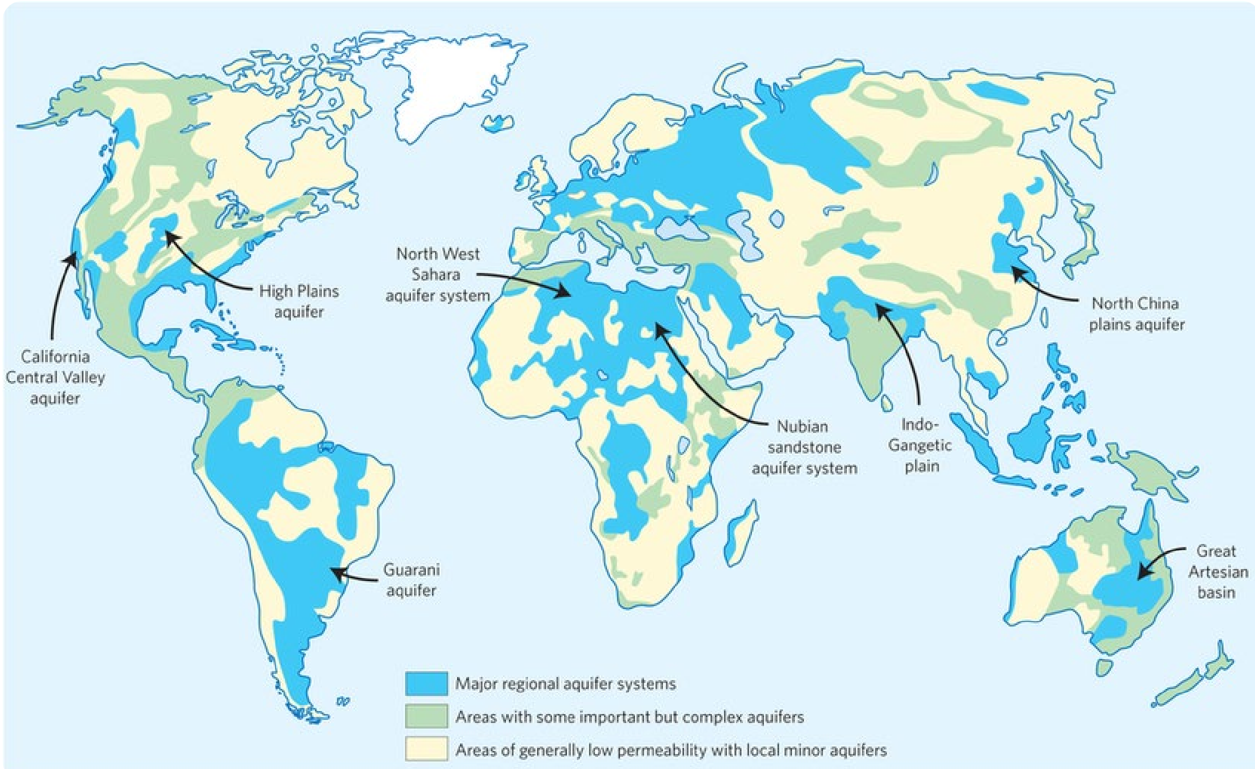


FIGURE 1. THE DISTRIBUTION OF WATER ON EARTH.

FIGURE 2. MAJOR GROUNDWATER AQUIFERS OF THE WORLD. COUNTRIES USING THE GREATEST VOLUMES OF GROUNDWATER INCLUDE INDIA, THE UNITED STATES, PAKISTAN, CHINA, IRAN, SAUDI ARABIA, AND MEXICO.

REPRINTED WITH PERMISSION FROM TAYLOR ET AL. (2013).[11]



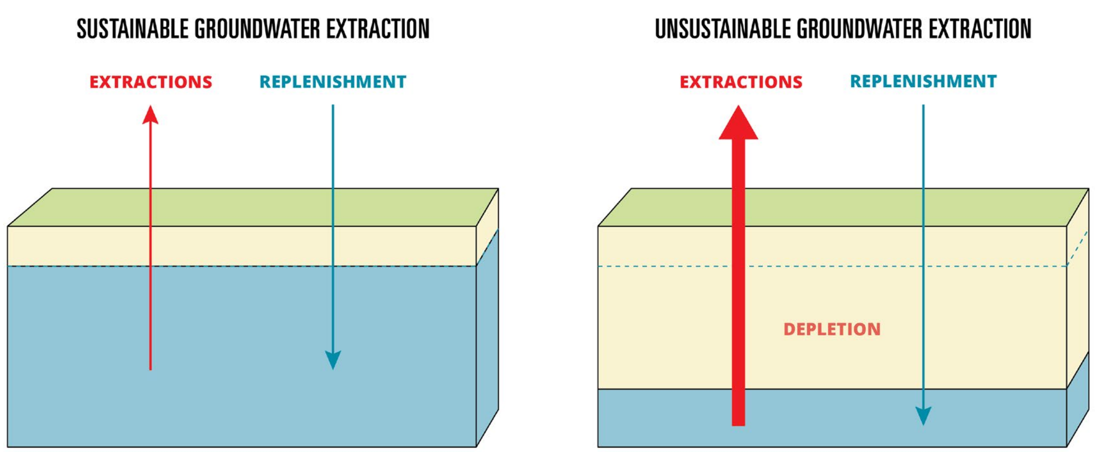


FIGURE 3. SUSTAINABLE VERSUS UNSUSTAINABLE GROUNDWATER EXTRACTION. WHEN GROUNDWATER EXTRACTION IS BALANCED WITH RENEWABLE REPLENISHMENT (LEFT), GROUNDWATER LEVELS WILL REMAIN DYNAMICALLY STABLE OVER TIME. HOWEVER, WHEN EXTRACTION EXCEEDS REPLENISHMENT (RIGHT), GROUNDWATER LEVELS WILL DECLINE, AND THE AQUIFER WILL BE INCREASINGLY DEPLETED.

Today, more than two billion people[12] and nearly half of all freshwater ecosystems[13] depend on groundwater for at least some of their needs. Groundwater also boosts food supply by providing 38% of the water used to irrigate crops.[14]

Unfortunately, in many places we are extracting groundwater faster than it is being replenished by natural or managed recharge. This overdraft is driving *groundwater depletion*, or a diminishing volume of water in aquifers—a fast-increasing problem around the world (Figure 3). Many regions that rely on groundwater do not regularly measure groundwater levels to detect overuse, and even more concerning, few governments have set controls to keep groundwater extraction at sustainable levels.

Even though the volume of groundwater remaining in an aquifer may be enormous, groundwater depletion can become a very serious problem long before an aquifer is fully emptied, simply because relatively small drops in the aquifer level can trigger myriad adverse impacts, as described in this report.

> "TODAY, GROUNDWATER SUPPORTS NEARLY 40% OF IRRIGATED CROP PRODUCTION, DRINKING WATER FOR MORE THAN TWO BILLION PEOPLE, AND MAINTAINS NEARLY HALF OF ALL FRESHWATER ECOSYSTEMS."

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2 AGRICULTURE'S DEPENDENCE ON GROUNDWATER

Everything we eat requires water for its growth. That's why more than 80% of all fresh water consumed for human enterprises goes to watering crops.[15]

Crop water may come from rainfall alone, or from a mixture of rainwater and supplemental *irrigation* water that is extracted from rivers, lakes, and aquifers. Of these various sources of water for crop production, rain accounts for 88% (Figure 4).[16]

However, local rainfall is insufficient for farming in many areas of the world, including countries that are the top producers of cereal and vegetable crops: the United States, China, India, and Russia. The ability to supplement rainwater with irrigation water is essential to farming in more than one-third of all river basins globally.

The importance of irrigation is illustrated by the fact that while only 16% of farmland globally is irrigated, that land accounts for 44% of all crop production, indicating that irrigated farms are more than four times more productive than rainfed farms. Irrigation allows for higher yields in a given crop cycle and for multiple crop cycles each year. As a result, large crop yields can be produced from relatively small areas of irrigated land.[18]

Nearly two-thirds (62%) of all irrigation water is extracted from rivers and lakes, and the remaining 38% is pumped from aquifers[19] (Figure 5). But this global average obscures the fact that some irrigation regions are almost entirely dependent on groundwater, and many other regions depend on groundwater to supplement surface water supplies. This is particularly true during droughts when river supplies are meager.[20] For instance, in the Central Valley of California (United States)—one of the most productive farming regions in the world—irrigation provides three-quarters of all the water consumed by crops. More than 40% of this irrigation water comes from groundwater, on average, but up to 70% of it comes from groundwater during droughts.[21] In the Indus River Valley of Asia, half of farm water comes from irrigation, and groundwater provides more than 40%.[22] In the Yellow River basin in China, farmers depend on irrigation for 44% of their water supplies, and more than 40% of that irrigation water comes from groundwater.

> "ONE-QUARTER OF IRRIGATED FOOD PRODUCTION RELIES ON UNSUSTAINABLE GROUNDWATER EXTRACTION, WHICH HAS HUGE IMPLICATIONS IN PLACES LIKE THE US, MEXICO, THE MIDDLE EAST AND NORTH AFRICA, INDIA, PAKISTAN, AND NORTH CHINA."

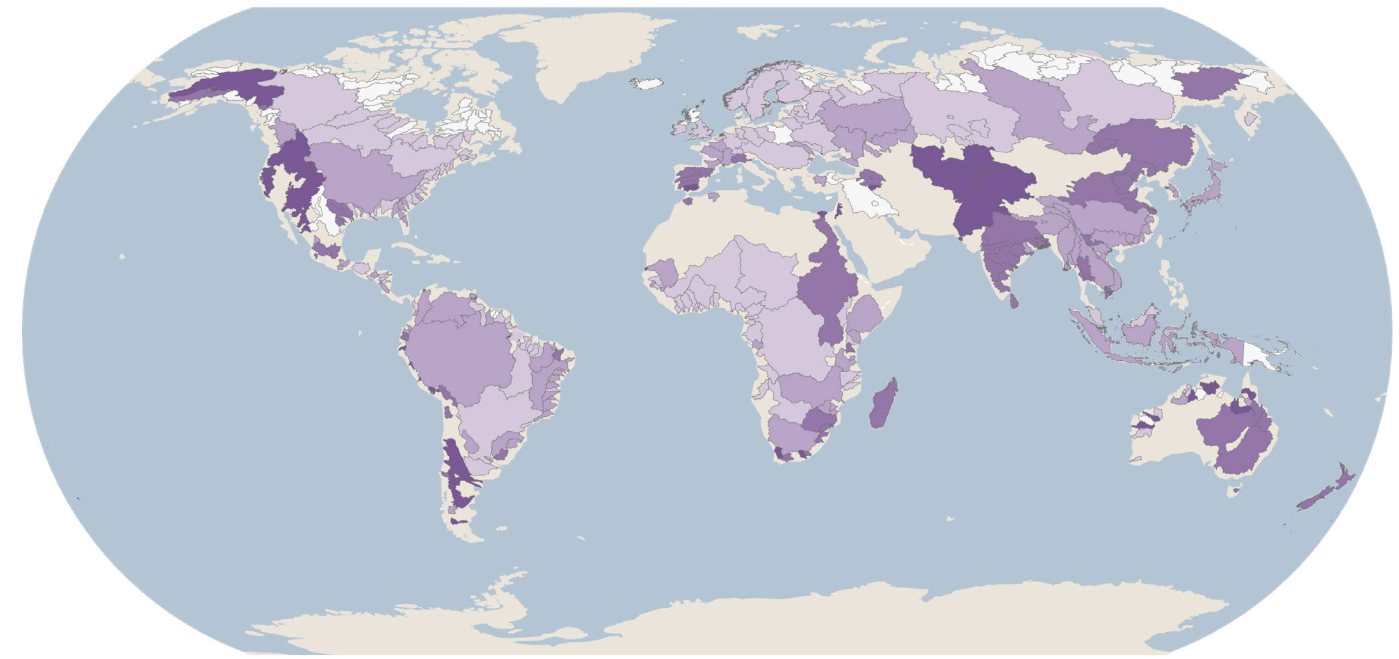

FIGURE 4. MAP SHOWING THE PERCENTAGE OF CROP WATER THAT COMES FROM RAINFALL VERSUS IRRIGATION IN EACH RIVER BASIN. DATA FROM MEKONNEN AND HOEKSTRA (2010).[17]

PERCENT IRRIGATED
- Little to no water use
- <2%
- 2% - 10%
- 10% - 30%
- >30%

PERCENT GROUNDWATER
- Little to no groundwater
- <3%
- 3% - 10%
- 10% - 25%
- 25% - 50%
- 50% - 75%
- >75%

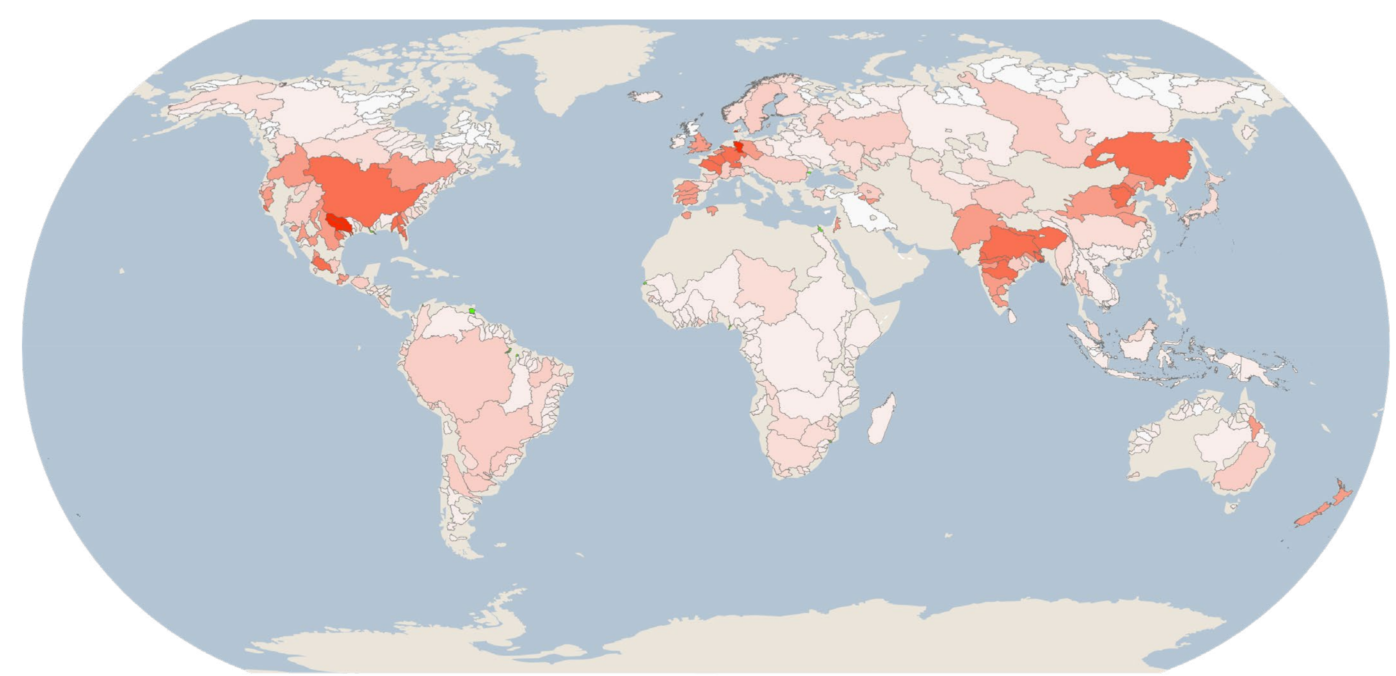

FIGURE 5. MAP SHOWING PERCENTAGE OF IRRIGATION WATER COMING FROM GROUNDWATER IN EACH RIVER BASIN. DATA FROM MEKONNEN AND HOEKSTRA (2010).[23]

3 GROWING UNSUSTAINABLY: TRENDS AND DRIVERS IN GROUNDWATER USE

Groundwater use has been increasing rapidly with the growth of human populations, changing diets, and expansion of cropland needed to feed more people (Figure 6). An estimated 70% of all global groundwater use goes to irrigated farms.[24]

A discussion of solutions to these global drivers of increasing water use is beyond the scope of this report; ultimately, sustainable groundwater management is achieved primarily through local or regional actions and decisions focused on individual aquifers. The key challenge in striving for sustainable groundwater management is to balance the rate of water extraction from an aquifer with its renewable replenishment.

> "THE KEY CHALLENGE IN STRIVING FOR SUSTAINABLE GROUNDWATER MANAGEMENT IS TO BALANCE THE RATE OF WATER EXTRACTION FROM AN AQUIFER WITH ITS RENEWABLE REPLENISHMENT, YET THIS CHALLENGE WILL GROW IN COMING DECADES DUE TO CHANGING CLIMATIC CONDITIONS."

CLIMATE CHANGE IS MAKING GROUNDWATER MANAGEMENT MORE DIFFICULT

The challenge of balancing groundwater use with aquifer replenishment will grow in coming decades due to changing climatic conditions. Warming air temperatures are already affecting the volume and seasonal patterns of precipitation, river flows, snowmelt runoff, and groundwater recharge. These ongoing and projected changes have important implications for water availability both now and in the coming decades:

→ *Changes in precipitation and temperature.* Notable decreases in precipitation have occurred during the past half-century within the latitudinal band from 10º South to 30º North, with pronounced regional drying in the western United States, Chile, northwestern India, southern Australia, western Europe, eastern Brazil, and northeastern China.[26] Decreases in annual rainfall, changes in rainfall timing (seasonality), and changes in the frequency of rainfall or drought can have major consequences for the viability of all agriculture—both irrigated and rain-fed—as these changes have created water deficits.

→ *Reductions in runoff, river flows, and groundwater recharge.* Warming temperatures are increasing evaporation from soils, snowpacks, and rivers, resulting in decreased groundwater recharge and reduced water availability. Due to rapid, widespread increases in water use over the past century, it is quite difficult to ascertain how much of the decline in river flow and aquifer levels can be attributed to climate change. However, climate model projections for the rest of this century forecast substantial decreases in water availability in many of the regions that are already experiencing the most severe water depletion: the Middle East, the western United States, southern Europe, southern Australia, Chile, Argentina, and southern Africa. As just one example, the Colorado River of the southwestern United States has already lost 10% of its river flow due to rising temperatures and increased evaporation, and it is expected to lose another 10%–25% by mid-century, according to climate scientists.[27,28] Reduced river flow, combined with continued heavy water consumption in the basin, has severely depleted once-massive water storage reservoirs, leading to governmental reductions in surface water deliveries to farmers. In response, farmers and cities are pumping more groundwater.

→ *Increases in groundwater demand.* Increasing temperature increases human demand for water, which is often met with more groundwater extraction, creating a vicious cycle of depletion. As temperatures continue to rise, yields for many crops will decline unless rainfall increases or supplemental irrigation can be applied to maintain suitable growth conditions or to prevent heat stress. A longer growing season resulting from warmer temperatures will also require more water to support many crops. Lessened rainfall, warmer temperatures, and increased drought frequency and duration are leading many farmers to begin irrigating for the first time and causing irrigation farmers to need more water for their crops.

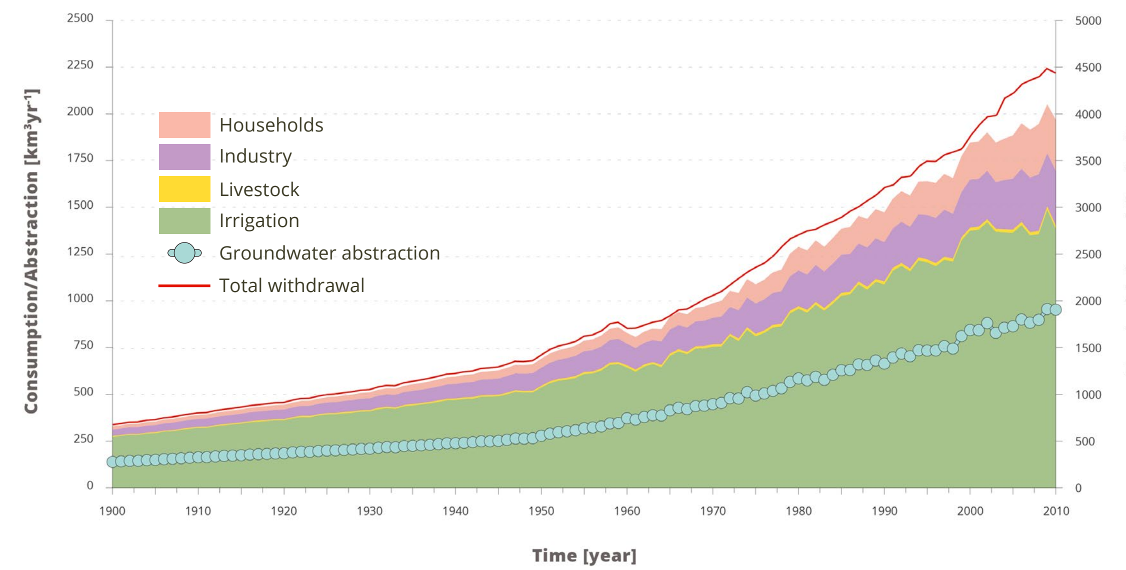

FIGURE 6. GROUNDWATER EXTRACTION TRENDS. GLOBAL GROUNDWATER EXTRACTION INCREASED FIVEFOLD OVER THE PAST CENTURY, WITH AN ACCELERATED INCREASE AFTER 1950 WHEN LARGE-SCALE INDUSTRIAL PUMPS CAME INTO WIDESPREAD USE. 'TOTAL WITHDRAWAL' REFERS TO USE OF BOTH GROUNDWATER AND SURFACE WATER. MODIFIED WITH PERMISSION FROM WADA (2016).[25]

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4 GROUNDWATER DEPLETION AND ITS CONSEQUENCES

In many aquifers around the world, groundwater is not being managed as a renewable resource; the rate of groundwater extraction is much greater than the rate at which aquifers are recharged by percolating rain, melting snow, and river seepage. This is known as "over-pumping" or "overdraft" or simply "depletion" (Figure 3). In some regions, shallower wells have gone completely dry, threatening food security and drinking water. As groundwater levels drop, more electricity is required to pump groundwater from the deeper levels, which means costs are higher; for many farmers, this becomes unaffordable, and so food security is threatened.

A growing portion of groundwater use is now deemed unsustainable, meaning that groundwater will not be replenished on human time scales.[29] Figure 7 shows the regions where groundwater levels have been falling rapidly in recent decades due to overdraft.

Alarmingly, more than one-quarter of the world's irrigated food production today relies on unsustainable groundwater extraction.[30] This groundwater depletion is concentrated in a few regions that rely heavily on overexploited aquifers to grow crops: the United States, Mexico, the Middle East, North Africa, India, Pakistan, and China. More than 40% of food grown in the United States depends on unsustainable groundwater use, and approximately one-quarter of food consumed in Turkey and Italy (including imports) depends on unsustainable, groundwater-dependent irrigation.[31] The primary crops associated with groundwater depletion include wheat, rice, sugar, cotton, and maize.

The North China Plain offers one of the most serious cases of large-scale aquifer overexploitation. In the past 60 years, the region's groundwater levels have dropped continuously at a rate of 0.5–2 meters per year.[32] The North China Plain contributes 40% of China's grain production, including two-thirds of the country's wheat output.

Loss of groundwater for farming can disrupt international food trade as well. [33] Eleven percent of global food trade depends on unsustainable groundwater use, primarily in Pakistan, the United States, and India. Most of the world's population lives in countries that source nearly all their staple crop imports from trade partners that deplete groundwater to produce these crops, highlighting the vulnerability of global food and water security.

When groundwater is managed sustainably, without its volume drawn down over time, it can provide an extremely useful "water savings account" that can be drawn upon during drought periods and then allowed to replenish during wetter times, thereby maintaining a dynamically stable level.[34] This important benefit is lost when the aquifer is consistently pumped faster than it can be replenished. Severe over-pumping of groundwater commonly occurs during droughts, when natural river flows are much reduced and easily exhausted by diversions for agriculture.[35] After river diversions are dried up, farmers will turn to groundwater pumping for their irrigation needs. Thus, agriculture can have the double impact of drying rivers and depleting groundwater aquifers at the same time.

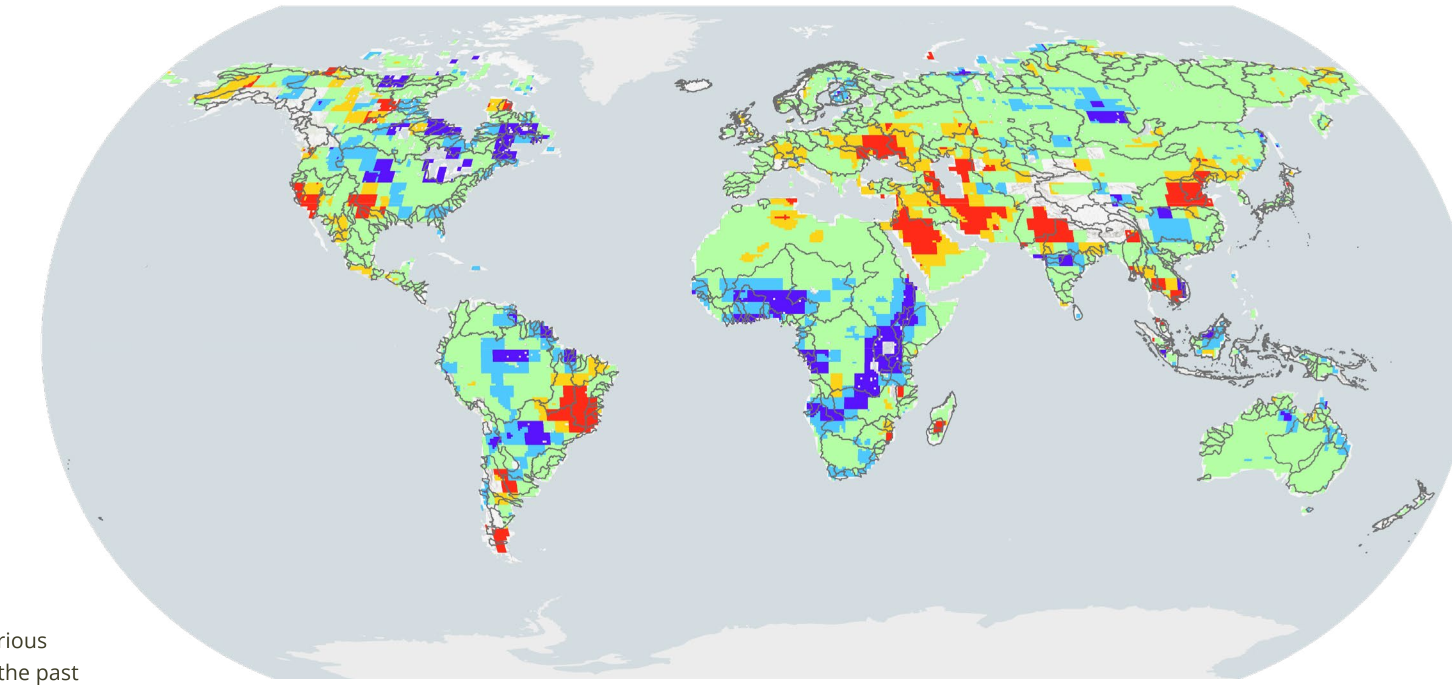

FIGURE 7. GLOBAL MAP OF GROUNDWATER STORAGE CHANGES SINCE 2002 FROM NASA GRACE (GLOBAL INSTITUTE FOR WATER SECURITY, UNIVERSITY OF SASKATCHEWAN). DATA AND GRAPHICS CONTRIBUTORS INCLUDE INGE DE GRAAF, XANDER HUGGINS, HRISHI CHANDANPURKAR, AJ PURDY, AND JAY FAMIGLIETTI.

CHANGE IN GROUNDWATER LEVEL (MM / YEAR)

- < -10
- -10 – -5
- -5 – +5
- +5 – +10
- > +10

ESRI, FAO, NOAA, USGS, ESRI, USGS

Groundwater depletion has a variety of additional impacts, discussed briefly below.

DRYING OF WELLS

When over-pumping lowers groundwater levels, both residential and irrigation wells can dry up.[36] Wealthier irrigators or homeowners may be able to drill deeper to continue accessing groundwater, or arrange for water to be delivered by truck or by connecting to a centralized water system; but poorer well owners are often left high and dry.[37]

Across the western United States, an estimated 1 in 30 wells have gone dry.[38] But that number, which might sound low, reflects an average across a vast geographic area and understates the severe effects of well drying on local communities. In Tulare County, California (United States), where massive volumes of water are pumped for irrigation and aquifer levels are dropping, more than 1,300 residential wells went dry during a drought between 2012 and 2016, forcing the state to provide temporary emergency drinking water supplies to residents.[39]

LAND SUBSIDENCE

Removal of groundwater stored in aquifers can cause serious problems at the land surface. When large volumes are pumped from an aquifer, once-saturated geologic layers can weaken and collapse, causing lowering or *subsidence* of the land surface. This can be very damaging to roads, buildings, and utilities.

Consider, for example, the Central Valley of California (United States), which covers about 52,000 km^2 and is one of the most productive agricultural regions in the world. More than 250 different crops are grown, with an estimated value exceeding US$20 billion per year. Extensive withdrawals of groundwater for irrigation led to widespread land subsidence in the Central Valley beginning in the mid-1920s. By the early 1980s, some areas had experienced subsidence of more than nine meters.[40] Bridges, roads, buried irrigation pipelines, and wells have been altered or damaged by subsidence. Between 1955 and 1972, destruction of local water-delivery and flood-control structures was particularly costly; a 2013 estimate put the cost at more than US$1.3 billion.[41]

Similarly, intensive groundwater pumping to irrigate pistachio farms in the Rafsanjan Plain of Iran has led to declines in groundwater levels of ~25 meters and land subsidence of nearly one meter, causing extremely expensive damage, including earth fissures and cracks in buildings and roads.[42]

SALTWATER CONTAMINATION OF GROUNDWATER AQUIFERS

In many coastal areas, groundwater flowing toward the ocean encounters underground areas where seawater has permeated geologic layers and sediments. The density difference between fresh groundwater and salty groundwater limits the mixing of the waters to some degree, with the heavier salt water sitting beneath fresh water. However, heavy groundwater pumping can disturb this transition zone, pulling salty groundwater inland and causing salt water to contaminate freshwater aquifers, making the water unsuitable for farm irrigation and for drinking water, among other uses. Rising sea level is exacerbating this problem.[44]

PUMPING WELLS CAN REDUCE THE FLOW OF RIVERS

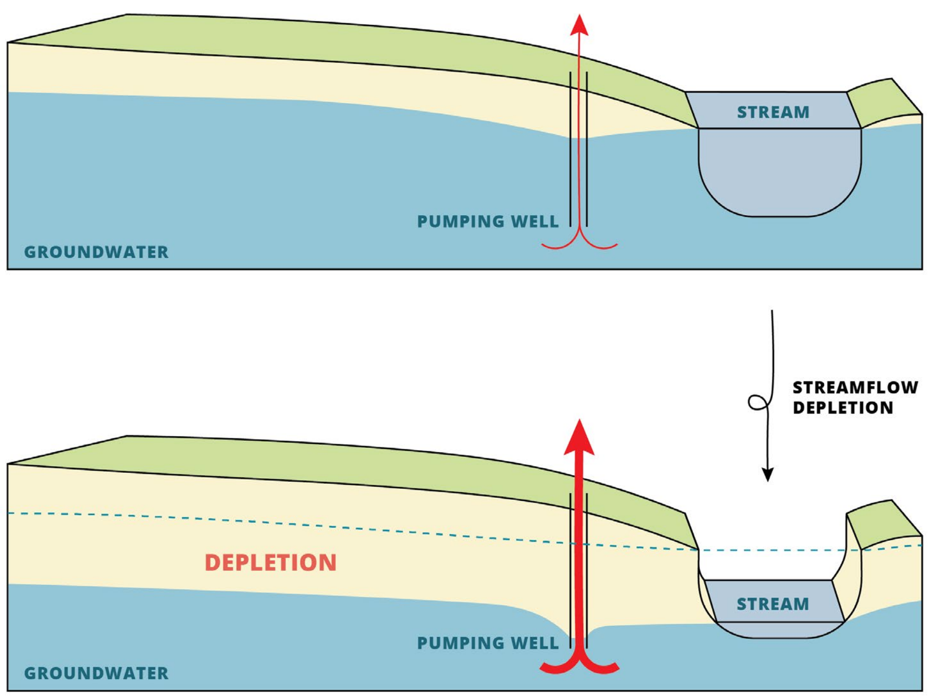

FIGURE 8. EFFECTS OF GROUNDWATER PUMPING ON RIVERS[43] ABOVE: WHEN A WELL PUMPS GROUNDWATER, SOME PORTION OF THE GROUNDWATER THAT WOULD HAVE OTHERWISE DRAINED INTO THE RIVER IS INTERCEPTED BY THE WELL, REDUCING STREAMFLOW. BELOW: UNDER HEAVY PUMPING OR AFTER LONG DURATION OF PUMPING, THE WELL CAN BEGIN SUCKING WATER DIRECTLY FROM THE RIVER, TYPICALLY RESULTING IN RAPID DEPLETION OF STREAMFLOW.

> “OVERDRAFTING GROUNDWATER RESOURCES IS PUTTING RIVER BASINS AT RISK—20% OF ALL RIVER BASINS HAVE DECREASED ECOLOGICAL FUNCTIONING AND MORE THAN HALF OF ALL RIVER BASINS ARE AT RISK BY 2050, IF CURRENT TRENDS CONTINUE.”

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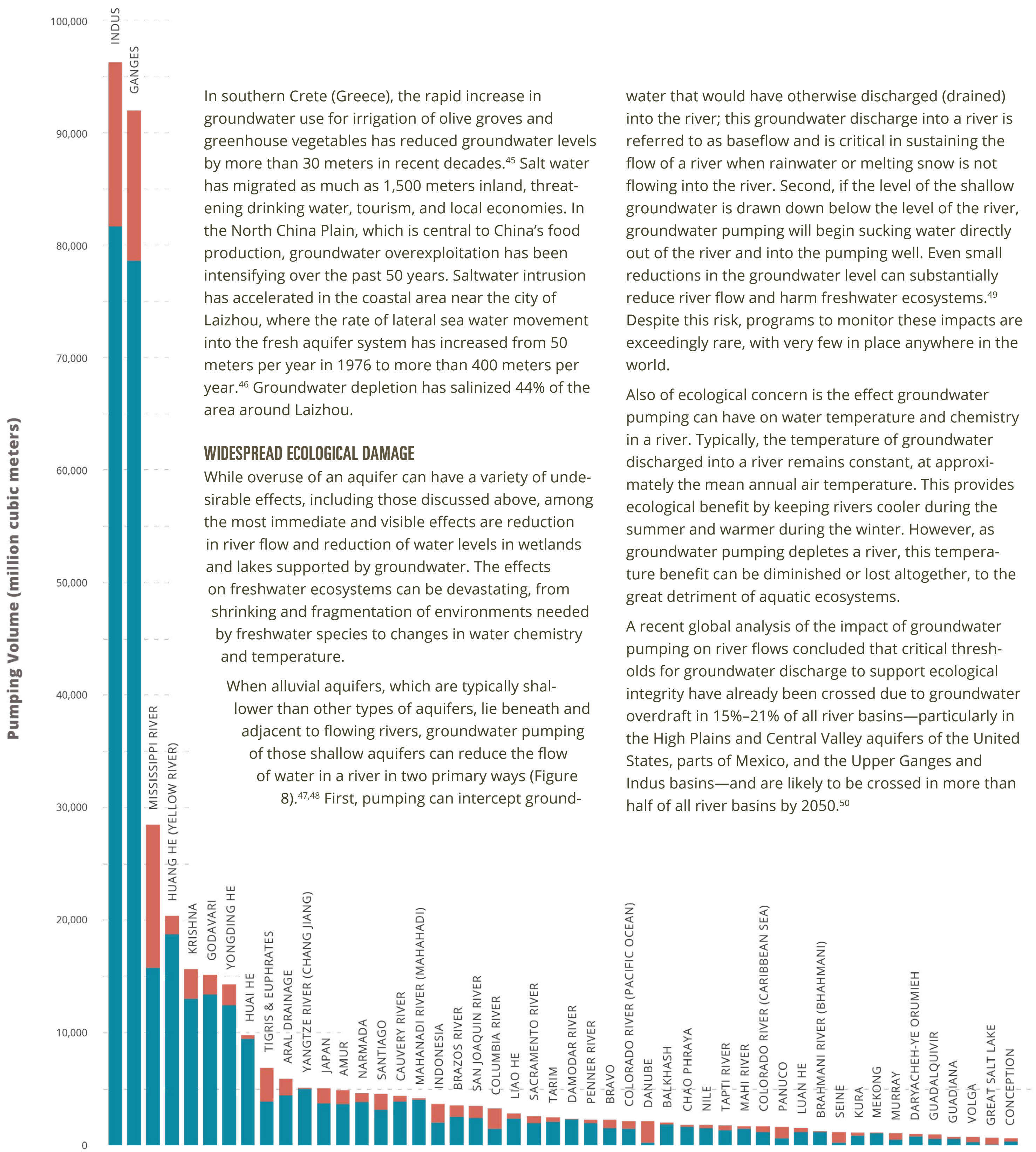

FIGURE 9. GROUNDWATER PUMPING IMPACTS ON RIVER FLOW. NEARLY HALF OF ALL GROUNDWATER PUMPING REDUCES RIVER FLOW; ONLY THE 50 RIVER BASINS WITH GREATEST VOLUMES OF PUMPING ARE SHOWN HERE. THE BARS SHOW THE TOTAL VOLUME OF GROUNDWATER PUMPED IN EACH RIVER BASIN, WITH THE RED PORTION INDICATING THE VOLUME THAT COMES FROM RIVER DEPLETION (CAPTURE). VOLUMES ARE SHOWN IN MILLION CUBIC METERS PER YEAR, AVERAGED FOR 1960–2010. DERIVED FROM MODEL OUTPUTS IN DE GRAAF ET AL. (2019).[55]

In southern Crete (Greece), the rapid increase in groundwater use for irrigation of olive groves and greenhouse vegetables has reduced groundwater levels by more than 30 meters in recent decades.[45] Salt water has migrated as much as 1,500 meters inland, threatening drinking water, tourism, and local economies. In the North China Plain, which is central to China's food production, groundwater overexploitation has been intensifying over the past 50 years. Saltwater intrusion has accelerated in the coastal area near the city of Laizhou, where the rate of lateral sea water movement into the fresh aquifer system has increased from 50 meters per year in 1976 to more than 400 meters per year.[46] Groundwater depletion has salinized 44% of the area around Laizhou.

WIDESPREAD ECOLOGICAL DAMAGE

While overuse of an aquifer can have a variety of undesirable effects, including those discussed above, among the most immediate and visible effects are reduction in river flow and reduction of water levels in wetlands and lakes supported by groundwater. The effects on freshwater ecosystems can be devastating, from shrinking and fragmentation of environments needed by freshwater species to changes in water chemistry and temperature.

When alluvial aquifers, which are typically shallower than other types of aquifers, lie beneath and adjacent to flowing rivers, groundwater pumping of those shallow aquifers can reduce the flow of water in a river in two primary ways (Figure 8).[47,48] First, pumping can intercept groundwater that would have otherwise discharged (drained) into the river; this groundwater discharge into a river is referred to as baseflow and is critical in sustaining the flow of a river when rainwater or melting snow is not flowing into the river. Second, if the level of the shallow groundwater is drawn down below the level of the river, groundwater pumping will begin sucking water directly out of the river and into the pumping well. Even small reductions in the groundwater level can substantially reduce river flow and harm freshwater ecosystems.[49] Despite this risk, programs to monitor these impacts are exceedingly rare, with very few in place anywhere in the world.

Also of ecological concern is the effect groundwater pumping can have on water temperature and chemistry in a river. Typically, the temperature of groundwater discharged into a river remains constant, at approximately the mean annual air temperature. This provides ecological benefit by keeping rivers cooler during the summer and warmer during the winter. However, as groundwater pumping depletes a river, this temperature benefit can be diminished or lost altogether, to the great detriment of aquatic ecosystems.

A recent global analysis of the impact of groundwater pumping on river flows concluded that critical thresholds for groundwater discharge to support ecological integrity have already been crossed due to groundwater overdraft in 15%–21% of all river basins—particularly in the High Plains and Central Valley aquifers of the United States, parts of Mexico, and the Upper Ganges and Indus basins—and are likely to be crossed in more than half of all river basins by 2050.[50]

For example, groundwater over-pumping from the High Plains Aquifer in the midwestern United States curtailed groundwater discharge into one-fifth of the region's rivers, thereby causing once-perennial rivers to dry completely between rainstorms. This loss of river flow drastically altered fish communities, particularly from disappearance of larger species.[51]

Another example comes from Egypt. In the 1960s, the Egyptian government started developing extensive irrigation programs in the Western Desert. This agricultural development was dependent upon fossil groundwater from wells drilled more than 300 meters deep into the Nubian Sandstone Aquifer. Heavy groundwater pumping since then has caused a rapid demise of ancient springs and oases that have supported unique biological communities and human civilizations for thousands of years.[52]

As shown in Figure 9, almost half of all groundwater pumping is already capturing river water, thereby reducing river flows.[53] Nearly half of all freshwater ecosystems are supported by groundwater discharge or by shallow groundwater levels within the rooting depth of plants.[54] The ecological consequence of these groundwater declines is a slow desiccation of the landscape.

5 MOVING TOWARD SUSTAINABLE GROUNDWATER MANAGEMENT

The technical and policy actions required to balance groundwater use with aquifer replenishment are conceptually simple (Figure 3). The requisite actions can be summarized in four general strategies: (1) **Measure and Manage** – collect and analyze local groundwater information to develop a sustainable management plan, including monitoring to verify the efficacy of the plan during implementation; (2) **Set Sustainable Limits** – set limits or "caps" on the total volume of groundwater that can be extracted from an aquifer, along with volumetric allocations to each user and monitoring and regulation of those allocations; (3) **Recharge and Replenish** – enhance aquifer recharge through natural or managed replenishment; and (4) **Reduce Demand and Maintain Balance** – manage demand and groundwater extraction to balance water use with replenishment.

While these key strategies are simple in concept, implementing them has proved difficult around the world due to failures in groundwater governance. The nature of those failures, as well as key features of successful governance systems, will be discussed later in this section. First, we will describe the four general strategies highlighted above, emphasizing that none of them will likely succeed without adequate investment in problem evaluation and monitoring to determine whether actions taken are having the intended benefits.

FIRST STRATEGY: MEASURE AND MANAGE

ANALYZE GROUNDWATER INFORMATION TO DEVELOP A SUSTAINABLE MANAGEMENT PLAN, INCLUDING MONITORING TO VERIFY THE EFFICACY OF THE PLAN.

We cannot adequately manage a natural resource such as groundwater if we don't understand how much we are using and how much is being replenished. Basic information about the inputs to and extractions from an aquifer is essential for sound, sustainable management. This requires investment in basic data collection and monitoring activities, as well as expert capacity to evaluate data and formulate a management plan. As a plan is implemented, monitoring data will enable the project managers to evaluate whether it is working as intended.[56] Case Study 1 (see section 7) describes the comprehensive monitoring program being implemented in Brazil and other South American countries.

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SECOND STRATEGY: SET SUSTAINABLE LIMITS

SET CLEAR LIMITS AND ALLOCATIONS FOR GROUNDWATER CONSUMPTION.

A fundamental tenet of sustainable water management is to expressly limit water consumption so that water sources are not depleted and freshwater ecosystems are not damaged.[57,58,59] Such a limit, or cap, on water use can be specified volumetrically, such as by dictating maximum total groundwater consumption on an annual or multi-year basis, or can be achieved by limiting water consumption based on aquifer levels.

Managing groundwater use within mandated limits requires clear specification of allocations—i.e., the quantity of groundwater that each user can extract.[60] Groundwater use cannot be controlled unless volumetric allocations are made to each user and the volume of water extracted is carefully monitored and regulated. Obviously, the sum of individual allocations must not exceed the cap on total groundwater consumption from the aquifer.

Given that groundwater pumping can affect river flows, lakes, and wetlands (Figures 8 and 9), limits on groundwater consumption should always be set at a level that sustains physical exchanges of water between groundwater and hydrologically connected ecosystems.

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→ EXAMPLE: TEXAS (UNITED STATES)

The evolution of regulatory policies governing the use of the Edwards Aquifer in Texas (United States) illustrates some of the ways groundwater limits can be specified. In response to a federal lawsuit brought by conservation organizations seeking to protect endangered species dependent on springs discharging from the aquifer, the Texas legislature in 1993 set a cap on groundwater withdrawals (550 million cubic meters per annum) to be achieved by 2004, and a lower limit of 493 million cubic meters by 2008.[61] The legislation also created a regulatory authority to enforce these limits. However, in 2007 the state changed its approach by specifying pumping reductions, ranging from 20% to 44%, that would be triggered as aquifer levels fell. Importantly, the effectiveness of these approaches in protecting endangered species populations has been closely monitored so that pumping restrictions can be adjusted as needed to sustain the species. Significant investment in land conservation to protect aquifer recharge zones has also been an important component of these efforts.

→ EXAMPLE: FRANCE

Efforts to protect a wetland ecosystem in France illustrate the effectiveness of combining a cap on total groundwater consumption with quantified allocations to each user.[62] The Beauce Aquifer is located between the Seine and Loire rivers, southwest of Paris. During a series of droughts between 1989 and 1992, the wetland of La Conie, sustained by the aquifer's high-water table, began contracting because of increased irrigation. An association for the protection of the La Conie wetland asked the federal government to impose measures to limit groundwater irrigation. In March 1995, the Beauce Aquifer Charter was signed between the administration and irrigator representatives. It set three thresholds associated with increasingly restrictive measures to maintain water table levels and environmental flows in rivers entering the wetlands. The specific allocations of water to individual users were set by an irrigators' association.

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> "THERE ARE MANY PROVEN SOLUTIONS TO OUR GROUNDWATER PROBLEMS, BUT THROUGHOUT ALL, STRONG WATER GOVERNANCE IS ESSENTIAL."

→ EXAMPLE: CALIFORNIA (UNITED STATES)

State legislation passed in California in 2014 illustrates how legislative mandates can facilitate local design of groundwater management strategies that limit consumption.[63] The state's Sustainable Groundwater Management Act (SGMA) set a state policy of sustainably managing groundwater resources. The law defines sustainability as "management and use of groundwater in a manner that can be maintained during the 50-year planning and implementation horizon without causing undesirable results." The act defined six undesirable results:

- → depletion of supply, indicated by chronic lowering of groundwater levels
- → reduction of groundwater storage
- → seawater intrusion
- → degraded water quality
- → land subsidence that substantially interferes with surface land uses
- → adverse impacts on the beneficial uses of interconnected surface water due to depletions

SGMA also mandates the establishment of local groundwater sustainability agencies to create aquifer management plans that serve the intent of SGMA. To date, 262 agencies have been established in 140 groundwater basins in the state.[64]

THIRD STRATEGY: RECHARGE AND REPLENISH

ENHANCE AQUIFER RECHARGE THROUGH NATURAL OR MANAGED REPLENISHMENT.

Sustainable extraction from an aquifer can be maximized by increasing the rate of aquifer replenishment. Here we highlight two of the most common ways to bolster aquifer replenishment.

MANAGED AQUIFER RECHARGE

Managed aquifer recharge (MAR) is the purposeful recharge of water into aquifers for later use or to serve other purposes.[65] MAR can increase the volume of an aquifer and raise the groundwater level, so groundwater is more accessible and less costly to extract; it can slow or block saltwater intrusion or land subsidence; and it can help restore groundwater discharge into a river or lake.

MAR can be accomplished either actively or passively. In active recharge, an injection well is used to pump water into, rather than out of, an aquifer. For example, properly treated wastewater from a city or an industrial plant can be pumped into an injection well to increase aquifer content. Passive approaches typically involve constructing infiltration basins that help maximize the amount of water moving into an aquifer. For example, rainwater runoff can be channeled into a constructed depression from which water can infiltrate into the aquifer, or small dams can be built along streams to slow water flow and allow more stream water to infiltrate into the aquifer.

The use of MAR globally has increased tenfold over the past 50 years, with more than half of these efforts being implemented in India and the United States. ,

MAR currently replenishes only 2.4% of global groundwater extraction, so it is not yet significantly impacting global groundwater depletion.[66] However, it can be a highly effective local solution.

→ EXAMPLE: NAMIBIA

Recharge basins were constructed downstream of the OMDEL dam in 1997 to recharge an alluvial aquifer in a very arid region.[67] The dam retains floodwater from the normally dry Omaruru River and allows settling of sediment before water is released to the downstream recharge basins to replenish the aquifer. This approach has made water available for irrigation systems.

→ EXAMPLE: MEXICO

In Mexico, work is underway to construct small rock dams and other structures in streams to slow river flows and induce greater infiltration into shallow aquifers, as described in Case Study 2.

→ NATURE-BASED SOLUTIONS

Another means of enhancing groundwater recharge is to restore degraded forest or grassland areas to enhance their natural ability to infiltrate rainwater, snowmelt, and river flows into an underlying aquifer. This has the advantage of restoring habitat quality while also benefiting communities dependent on groundwater.

→ EXAMPLE: PAKISTAN

Case Study 3 describes ongoing work in Pakistan that is supported by corporate water stewardship programs.

→ EXAMPLE: CALIFORNIA (UNITED STATES)

In California, the Department of Water Resources is pursuing a program called Flood-Managed Aquifer Recharge, which promotes infiltration of floodwaters on both managed (e.g., flood bypasses) and unmanaged (e.g., natural) floodplains as well as on wildlife refuges and croplands that can be intentionally flooded. Many of these areas that flood naturally or through managed flooding can contribute to both flood-risk reduction and groundwater replenishment, along with having a range of other values promoted by floodplains.[68]

FOURTH STRATEGY: REDUCE DEMAND AND MAINTAIN BALANCE

MANAGE DEMAND AND GROUNDWATER EXTRACTION TO RESTORE BALANCE WITH AQUIFER REPLENISHMENT.

In many regions around the globe, a reduction in total groundwater use is desperately needed to arrest and reverse aquifer depletion.

When a cap is set lower than the current level of water use—suggesting that reductions in groundwater use are necessary to restore balance in an aquifer—it can be a powerful driver for conservation, particularly if farmers are financially incentivized. Below, we highlight a few strategies and incentives that have proven successful.

→ FARMLAND FALLOWING

One of the most reliable and effective ways to reduce groundwater use is to reduce the area being irrigated with groundwater.[69] One way to achieve this is by curtailing farming altogether on some portion of the farmland, either temporarily or permanently. The following examples illustrate the use of fallowing to reduce groundwater consumption.

→ EXAMPLE: TEMPORARY FALLOWING IN COLORADO (UNITED STATES)

A special groundwater management district was formed in the San Luis Valley of Colorado in 2009 for the purpose of collecting pumping fees that could be used to compensate farmers willing to temporarily fallow their farmland. The pumping fee revenues were supplemented by a federal farm conservation program, and between 2012 and 2013, a 30% reduction in pumping was achieved.[70] By 2016 the aquifer was recovering, and 4,000 hectares out of a targeted 11,000 hectares had been fallowed. Unfortunately, drought conditions have intensified in recent years, and the district has had to raise its pumping fees to encourage more farmers to participate in the fallowing program.

→ EXAMPLE: PERMANENT FALLOWING IN CALIFORNIA (UNITED STATES)

Retiring farmland permanently may be a necessary strategy when groundwater use must be reduced for the long term. However, great care needs to be taken to ensure this does not endanger food security or tear the social and economic fabric of local farming communities. This requires foresight and planning. The Sustainable Groundwater Management Act in California, which calls for protecting the state's aquifers, may require fallowing as much as 20% of the 2 million hectares of farmland in the San Joaquin Valley.[71] This possibility has stimulated much discussion about how to prioritize lowest-value farmland for retirement and about repurposing fallowed lands for wildlife and endangered species habitat,[72] solar power generation,[73] or rainfed pastureland.[74]

→ SHIFTING TO CROPS REQUIRING LESS IRRIGATION

Another way to reduce the area of irrigated land is by switching to production of rainfed crops (crops that do not require irrigation) or to crops that simply require much less water, whether irrigated or not, thereby saving substantial volumes of water while enabling farmers to sustain or even increase their agricultural revenues.[75,76] Such crop shifting can entail upfront capital costs for converting farm fields from one crop type to another and may in some require expenditures on new farm machinery or irrigation infrastructure to enable more efficient irrigation of the new crop type. But despite the costs, these conversions can yield attractive revenue and water benefits in many cases.


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→ EXAMPLE: CHINA

In response to a persistent, decade-long drought that began in 1999 and the loss of more than half of Beijing's municipal reservoir storage capacity, the Beijing Municipal People's Government entered into an agreement with upstream farmers in the Chaobai River basin to shift from paddy rice irrigation to dryland crops (primarily corn) in an effort to increase water flows into the Miyun Reservoir.[77] Nearly 7,000 hectares were enrolled in the program, which has paid farmers 8,250 yuan (about $1,244 USD) per hectare per year, resulting in a net profit of more than 33% for farmers. The project resulted in increased flows to the Miyun Reservoir of 29 million cubic meters per year.

→ IMPROVING IRRIGATION EFFICIENCIES

In theory, applying water more carefully and efficiently on croplands should result in a net reduction in water use, and in fact many field-scale experiments have documented this potential.[78] For example, field trials have documented water savings from shifting irrigation applications from furrow (flood) to sprinkler or drip irrigation, changing irrigation timing or scheduling, and improving water delivery infrastructure to reduce leakage or evaporation.

However, attempts to reduce water use at the level of farming districts, whole aquifers, or entire river basins through efficiency improvements have been almost uniformly unsuccessful, mainly because farmers will use any saved water to expand their irrigated area or grow more crops, in most cases *increasing* water use rather than saving water.[79] This is now called the "irrigation efficiency paradox"[80] and is a clear illustration of failure in water governance.

Successfully reducing water use through improved equipment, technology, or farm practices requires very careful accounting, monitoring, and enforcement—particularly in disallowing increases in crop production—which has often proved difficult for water managers or governments. Case Study 4 details a rare success story: a case study in which water savings from irrigation improvements did enhance environmental flows in a river in India. Such results can only be realized through meaningful dialogue and engagement of local water users, with explicit agreements about the fate of any saved water.

Ultimately, any investment in irrigation efficiency must be accompanied by monitoring and regulation of how much water comes out of each well or is delivered into each ditch or canal, so that real savings can be accomplished.

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THE CHALLENGES OF GROUNDWATER GOVERNANCE

As stated at the beginning of this section, implementing the four strategies discussed above may appear to be straightforward and conceptually simple. But around the globe, political leaders, water managers, and local communities have struggled mightily in their efforts to manage groundwater sustainably due to failures in water governance.[81,82]

Governance is a complicated and robust concept packed with meaning.[83] In essence, water governance refers to the work of the individuals, agencies, and institutions to shape the laws, policies, and plans that influence the management and allocation of water in any particular area.

When water governance is working well, everyone has sufficient clean and affordable water supplies to support their livelihoods and well-being, and native freshwater ecosystems remain diverse and healthy. Governance is seldom discussed in day-to-day water management and use until something goes wrong.

Water governance can go wrong in myriad ways. Failures are often blamed on inadequate funding, lack of expertise, lack of monitoring or willingness to enforce rules, lack of coordination among agencies, and all-too-widespread corruption.[84,85] However, governance also fails when local communities—particularly poor or otherwise marginalized groups—lack the opportunity to express their concerns and ideas, and when those governing the water system do not address those concerns in an honest, earnest, fair, and equitable manner.[86] All of these shortcomings can be greatly compounded when multiple jurisdictions are involved, such as when "transboundary" aquifers span multiple geopolitical jurisdictions.

Unfortunately, even when reform is needed, it is often difficult to initiate until water problems have become very serious. However, a water crisis can stimulate cooperative agreements and collaborative programs, including new institutions, among state regulators and the farmers and other groundwater users sharing an aquifer.[87,88] These arrangements provide an essential forum for the critically important dialogue, analysis, and planning necessary to develop a shared vision and to successfully implement solutions. Some illustrative examples are provided below.

→ EXAMPLE: SOUTH AFRICA

Case Study 5 describes the formation of a new water-sharing partnership among groundwater users in the Cape Town (Table Mountain) area of South Africa, created in response to the 2015–2019 "Day Zero" water shortage crisis.[89]

→ EXAMPLE: COLORADO (UNITED STATES)

In the San Luis Valley of Colorado, farmers are facing the possibility of having their wells shut down by the state engineer due to unsustainable use of the aquifer underlying their valley. In 2009, they collectively decided to form a special groundwater management district that imposes a pumping fee on all irrigators using groundwater.[90,91] These fees are used to compensate farmers willing to temporarily fallow their crop fields to reduce groundwater use. The district's goal is to reduce overall farm acreage by an average of 27% annually.

→ EXAMPLE: NEBRASKA (UNITED STATES)

In response to a severe drought in the 1950s, Nebraska passed a groundwater conservation law that enabled creation of local natural resources districts (NRDs) and authorized the NRDs to establish corrective measures to ensure proper conservation of groundwater.[92] Twenty-three NRDs have been formed, and each has a governing board (with between five and 21 members) that conducts groundwater management planning.[93]

A subsequent law passed in 2004 requires many of the NRDs to cooperatively develop integrated management plans to specify how hydrologically connected groundwater and surface water will be jointly managed. The stated purpose of integrated plans is to set "[c]lear goals and objectives with a purpose of sustaining a balance between water uses and water supplies so that the economic viability, social and environmental health, safety, and welfare of the river basin, subbasin, or reach can be achieved and maintained for both the near term and the long term."

Case Study 6 provides more detail on Nebraska's statewide approach to groundwater management.

In the Upper Republican River NRD, groundwater allocations are determined for a multiyear period (typically for five years), and the allocations have gradually decreased over time to reduce groundwater depletion. Initial water allocations were 5,610 cubic meters/year/hectare, and current allocations are 3,315 cubic meters/year/hectare.[94] The expansion of farm area is controlled, with a cap on total water use. The allocations are assigned to each field based on the size of the field.

6 SUMMARY TAKEAWAYS

While groundwater has been referred to as "hidden" water, its ecological and socioeconomic benefits can be seen everywhere. Nearly half of all freshwater ecosystems are supported to some degree by groundwater. Nearly 40% of all irrigated crop production depends on groundwater, and more than two billion people depend on groundwater for drinking water.

Only a small percentage of the world's aquifers are being managed for sustainability. Over-extraction of groundwater is occurring around the world, and groundwater depletion is having serious impacts on local communities, food security, drinking water supplies, and freshwater ecosystems.

More than one-quarter of the world's irrigated food production is currently dependent upon unsustainable groundwater extraction.

Strong water governance is essential to sustainable groundwater management, which is necessary to ensure that everyone has sufficient clean and affordable water supplies to support their livelihoods and well-being and that native freshwater ecosystems remain diverse and healthy. A key characteristic of strong governance is the ability to accurately monitor water availability and use and measure the effectiveness of groundwater management programs.

There are many proven solutions to our groundwater problems. Four general strategies are of paramount importance: (1) Measure and Manage—monitor, measure, and manage groundwater resources; (2) Set Sustainable Limits—set limits (or caps) on the total volume of groundwater that can be extracted from an aquifer as well as volumetric allocations to each user, and monitor and regulate those allocations; (3) Recharge and Replenish—enhance aquifer recharge through natural or managed replenishment; and (4) Reduce Demand and Maintain Balance—manage demand and extraction to balance water use with aquifer replenishment.

Partnerships among water users are critical not only to improve governance but also to create a platform where those concerned about water in their area can voice their concerns. Partnerships help ensure that typically marginalized groups have access to the dialogue and decision-making processes that affect their livelihoods and well-being.

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7 CASE STUDIES

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CASE STUDY 1: BRAZIL

MAPBIOMAS: MONITORING WATER CONDITIONS TO INFORM WATER PLANNING AND CONSERVATION

More than half of all freshwater resources in South America can be found in Brazil.

MapBiomas is a collaborative network of non-governmental organizations, academic institutions, and technology start-ups that uses scientific information to evaluate environmental changes in Brazil. In 2021, MapBiomas launched a new surface water dataset[95] for the country. The researchers reconstructed a time series of monthly surface water conditions since 1985, processing more than 180 thousand Landsat scenes in Earth Engine. The surface water database allowed the MapBiomas team to reconstruct surface water dynamics and measure land-to-water transitions over time.[96]

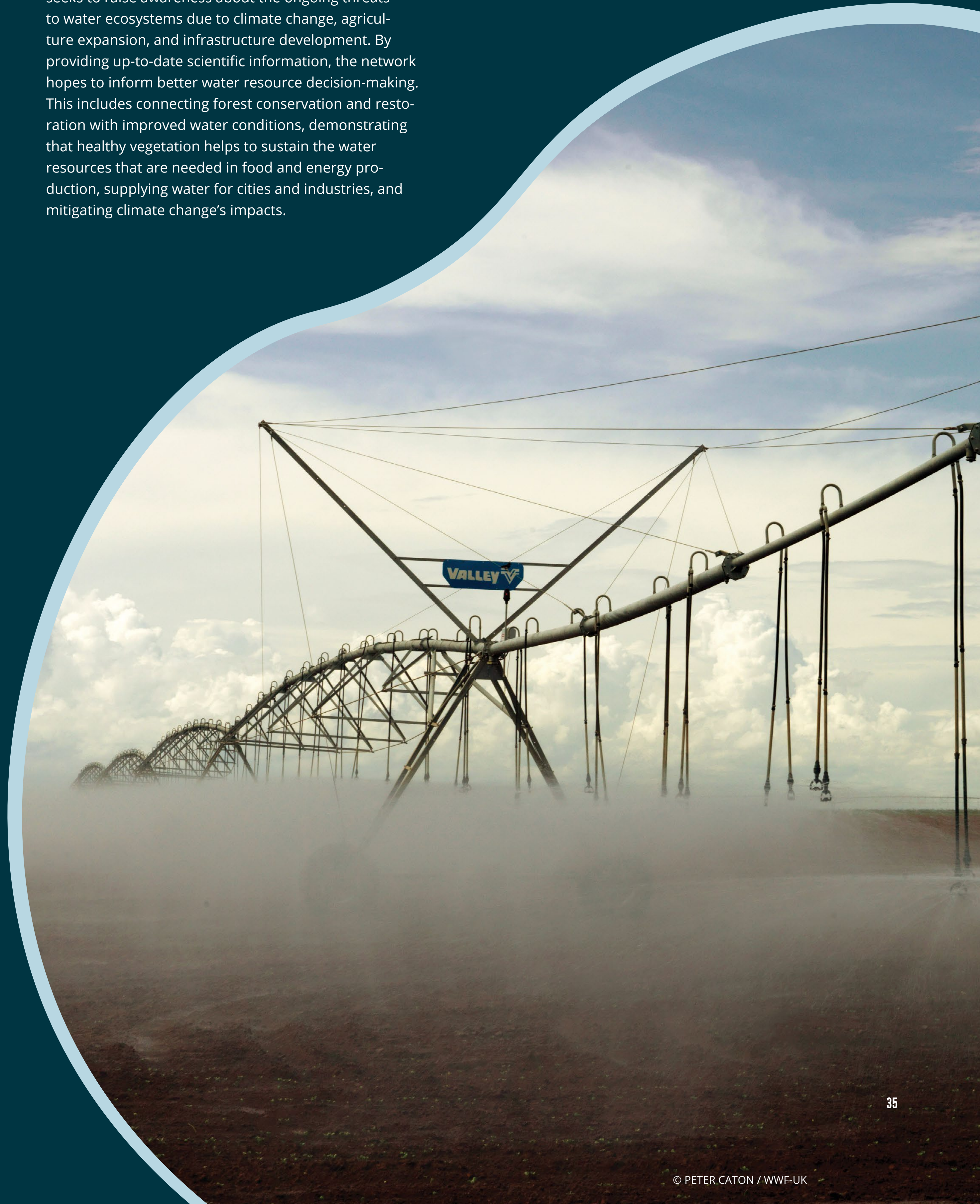
MapBiomas is now expanding its water monitoring on several fronts. In partnership with researchers at Princeton University, a new assessment of the dynamic interconnections between groundwater and surface water has been initiated. A pilot analysis was conducted in the São Francisco watershed (641,000 km2), an area undergoing rapid crop expansion, particularly for soybean plantations. Farmland in the São Francisco watershed expanded six-fold to 3.5 million hectares between 1985 and 2020, resulting in conversion of 12% of the natural vegetation in the basin. The pilot study found that both groundwater and surface waters are being depleted in the São Francisco basin due to climate change and agricultural expansion.

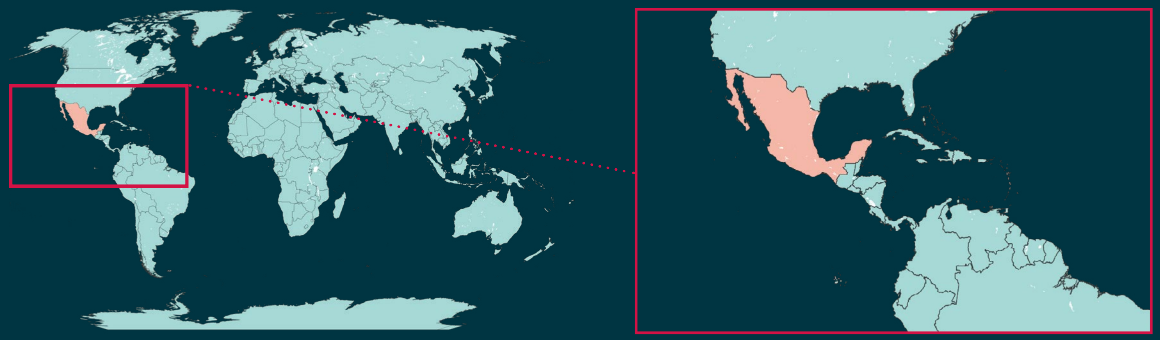
MapBiomas is now expanding its water monitoring efforts to the entire South American continent. The team mapped all tropical Andean glaciers between 1990 and 2020 and found an astonishing loss of 42% of the total glacier area.[97]

The expansion of MapBiomas efforts across South America will enable the team to identify climate change, agriculture, and infrastructure threats to water ecosystems and to better understand societal impacts, especially on food and energy production and access to water. The MapBiomas Water Project is already in place in the Pan-Amazonia region, including Bolivia, Colombia, Ecuador, French Guiana, Guyana, Peru, Suriname, and Venezuela, and additional partners are being recruited to cover the entire continent. Their collective strategy includes:

- → Selecting country partners and training local analysts to map and monitor water.
- → Building a dashboard to provide full access to data and statistics about water extent and dynamics.
- → Connecting the MapBiomas dashboard with end-users by conducting workshops to collect ideas and feedback for the dashboard.
- → Integrating the dashboard with the official water monitoring database in Brazil, connecting the surface water database with officially registered water bodies.
- → Implementing a communication strategy to engage people in climate change mitigation and adaptation policies.

Through this collective impact strategy, MapBiomas seeks to raise awareness about the ongoing threats to water ecosystems due to climate change, agriculture expansion, and infrastructure development. By providing up-to-date scientific information, the network hopes to inform better water resource decision-making. This includes connecting forest conservation and restoration with improved water conditions, demonstrating that healthy vegetation helps to sustain the water resources that are needed in food and energy production, supplying water for cities and industries, and mitigating climate change's impacts.





CASE STUDY 2: MEXICO

WWF-MEXICO: ENHANCING AQUIFER RECHARGE IN CHIHUAHUA, MEXICO

Aquifer depletion is a very serious challenge in Mexico, where 275 of the country's 653 aquifers have water deficits, according to formal decrees from Mexico's National Water Commission.[98] Over-drafting of aquifers is most severe in the arid northern states such as Chihuahua, where 42 of 61 aquifers are being rapidly depleted. The Chihuahuan water agency estimates that water extractions exceed natural recharge by 2 to 9.5 times in the over-drafted aquifers.[99]

Aquifer depletion in Chihuahua is creating a chain of severe impacts for the state's 3.55 million people.[100] Virtually the entire population uses groundwater as their main water source. Over-pumping aquifers can pull contaminants from deeper geologic layers into wells, polluting drinking water with arsenic, fluoride, lead, and other metals of natural origin; these contaminants are all frequently present with concentrations above the Official Mexican Norm for Drinking Water (NOM-127-SSA1-1994).[101] Groundwater depletion is not only causing drinking water contamination but creating adverse economic impacts, desertification, and biodiversity losses, especially among freshwater fishes and riparian ecosystems.

The future looks even worse, unfortunately. Arid conditions are expected to intensify as cyclic drought events and climate change diminish already scarce water resources. A climate change impact study done by WWF-Mexico shows that the Chihuahua's agricultural sector might need to increase water use by 20% to avoid crop stress as air temperature increases between 2° and 3° C.[102]

WWF is working with government entities and other partners throughout Mexico to build capacity for lasting aquifer conservation by implementing Integrated River Basin Management programs, with a focus on aquifer recharge involving rainwater capture and infiltration. The techniques to increase groundwater recharge feature "nature-based solutions" (NbS), in which the ability of natural ecosystems to provide important hydrological and ecological functions is protected and enhanced. NbS are essential in building climate change resilience; WWF-Mexico uses this approach in all pilot projects, as it benefits people and nature in a way that is sustainable and cost-effective in the long term.

"Maximum aquifer recharge" is one of the NbS strategies being implemented in Chihuahua. It aims to restore aquifer levels by conserving the main areas of rainwater capture, protecting the main aquifer recharge zones, developing geohydrological studies to understand water infiltration and aquifer recharge processes, and offering payments for environmental services provided by local communities. A key feature of the effort is the active engagement of community members in training programs to build human capacity for implementing the strategy, supporting water programs in local universities, and developing rainwater recharge projects. Demonstration projects are implemented first, to test the technical feasibility of rainwater infiltration and aquifer recharge in micro-basins and temporary stream beds.

Examples of these activities include soil and water conservation in the Sierra Tarahumara, where rainwater is captured on the roofs of Indigenous homes. In desert regions, these projects emphasize the need to reduce and control the intensive pumping of aquifers, along with the need to modernize irrigation techniques in agricultural areas. Community participation in recharging water is promoted through various communication strategies. These projects are made possible through the long-term collaboration of WWF-Mexico with the Gonzalo Rio Arronte Foundation, The Coca Cola Foundation, and Arca Continental.

CASE STUDY 3: PAKISTAN

WWF-PAKISTAN AND CORPORATE PARTNERSHIPS

Groundwater management is not yet receiving sufficient attention in Pakistan. Discussion around water usually begin and end with surface water flows in the Indus basin, which is the primary source of water for agriculture and hydropower. However, the region has increasingly relied on groundwater in the past few decades, resulting in widespread aquifer depletion.

Ironically, groundwater pumping started in the country in the 1960s to address problems associated with waterlogged soils in farming areas. The government of Pakistan introduced a scheme named Salinity Control and Reclamation, in which farmers received subsidies to install and pump wells; this was meant to eliminate water-logging by lowering the shallow groundwater level. In subsequent years, electricity costs were subsidized by the government, and groundwater pumping became a widespread practice to fill gaps in irrigation needs that could not be met by surface water supplies alone.

Pakistan now has more than one million wells, and groundwater declines are severe in many areas including many cities in the Punjab province. Rapid urbanization in this country of 220 million people has meant a greater reliance on groundwater for cities across Pakistan, resulting in depletion of groundwater aquifers. There are virtually no checks or regulations limiting the amount of water that is being extracted, so the situation is dire in terms of sustainability of the precious groundwater aquifers in the semi-arid country.

WWF-Pakistan has embarked on a series of pilot projects to address this issue, particularly in association with the private sector. WWF-Pakistan has been a pioneer in promoting the "water stewardship" approach with corporate partners. A few examples of water stewardship and replenishment projects are given below.

Community Water Stewardship: Replenishing Groundwater Resources in Lahore and Multan (Funded by PepsiCo)

WWF-Pakistan started working with PepsiCo International in 2019 to promote water stewardship and replenishment projects. The purpose of this program is to sustain groundwater aquifers by installing artificial recharge wells using rainwater capture in the city of Lahore. In 2021, a large groundwater replenishment system was designed for water catchment in the Lahore and Multan districts; this system has the potential to replenish 331,000 cubic meters of water annually by 2024. As of July 2022, a total of 114,374 cubic meters of groundwater had been replenished as part of this initiative. The initiative uses recharge wells that filter rainwater using best management practices and then injects the water into the aquifer. The key outcomes of the initiative include not only the harvested rainwater but also a growing awareness among local community members of the importance of water conservation and reuse.

Another important aspect of this project is its real-time monitoring system for aquifer water quality. Automatic sensors enable it to serve as an early warning system detecting anomalies in the water.

Integrated Watershed Management and Livelihood Improvement in Selected Sub-Catchments of Khanpur Dam (Funded by Coca Cola)

Khanpur Dam and its reservoir are located on the Haro River near the town of Khanpur in Khyber Pakhtunkhwa Province, about 40 km from Islamabad, the capital city of Pakistan. The dam was built in 1983 to provide drinking water for Islamabad, Rawalpindi, and other small towns, and also to irrigate 14,765 hectares of agricultural land. This project, which ran from 2018 to 2020, focused on stakeholder sensitization in regard to water conservation, stabilization of degraded slopes through nature-based solutions, and groundwater recharge through rainwater harvesting ponds and injection wells.

Approximately 97,000 cubic meters of groundwater were replenished in this project, which used afforestation techniques, improved farm tillage, and horticultural techniques to reduce runoff and keep water in place longer, allowing absorption into the ground. Development of pits, ponds, and wells resulted in further accumulation of over 18,000 cubic meters of groundwater. This project demonstrated the effectiveness of nature-based solutions for groundwater conservation and sustainability.

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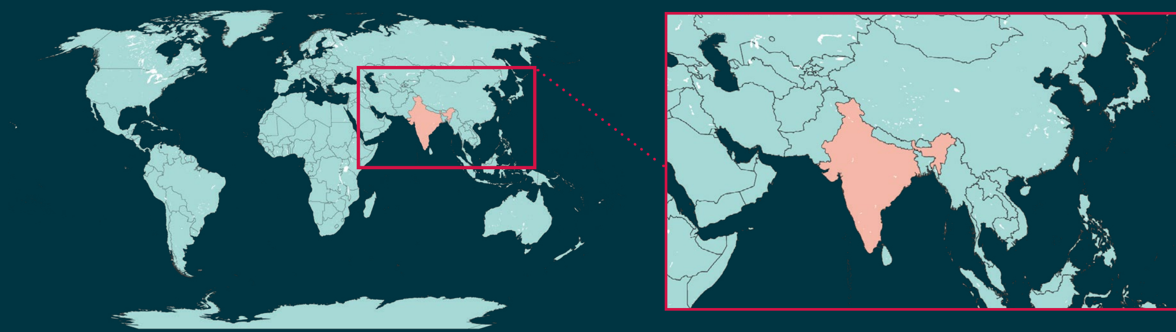


CASE STUDY 4: INDIA

WWF INDIA: RECOVERING ENVIRONMENTAL FLOWS IN THE KARULA RIVER

Heavy agricultural consumption of both river water and groundwater have greatly diminished water flows in many rivers in India. The country pumps more groundwater than any other nation, and nearly 80% goes to irrigating farmland.[103]

From 2017-2021, WWF-India worked with farmers, the Irrigation and Water Resources Department, and the District Administration of Bijnor in the state of Uttar Pradesh on an effort to demonstrate opportunities for enhancing flows in the Karula River, which flows into the Ramganga River and then into the Ganges River in northern India. This collaboration is testing the question: **"Can we help secure environmental flows in the river through interventions in the irrigation sector, while maintaining sustainable and enhanced water and land productivity levels, with improved overall agricultural production?"**

The effort has focused on water conservation (demand reduction) strategies in a farming area that receives surface water from the Khanpur Minor canal system, supplied from the Ramganga River. More than two-thirds of water use in this area goes to irrigating sugarcane, a very water-intensive but lucrative crop. The project team is hoping that by enhancing water use efficiency and thereby reducing water use in this farming area, more water will remain unused within the Khanpur Minor canal, and then flow into the Karula River.

A three-pronged approach guides the project activities:

→ demand-side management involving the promotion and adoption of more efficient irrigation practices to save water

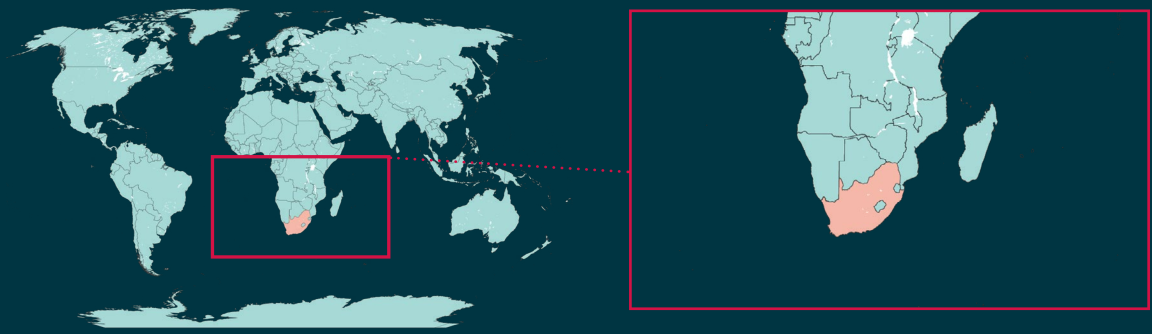
→ supply-side management involving the rehabilitation of the entire canal system of Khanpur Minor

→ institutional strengthening including establishment and capacity building of a water users association

The latter bullet point has been central to all work conducted to date. Stakeholder engagement is seen as a means of improving water governance, and much effort was expended at the start of the project to better understand the farm community by gathering information on the farmers' landholdings, typical cropping cycle and cropping patterns,modes of irrigation, agricultural yields, input costs, profit margins, the status of canals and allied infrastructure, and more. Stakeholders and farmers were also sensitized and motivated to enroll as Ramganga Mitras-friends of the Ramganga River, to collaborate and contribute to river rejuvenation efforts. One of the important tasks was to physically connect the tail end of the canal to the Karula River, thereby enabling any saved water to be released into the Karula.

Working closely with both farmers and water managers, the project team then identified a package of "Better Management Practices" (trench based sugarcane planting, *amrit paani* (bio pesticide), *amrit khaad* (biofertiliser), and micro nutrient application) that was promoted for farmer adoption. One of the key improvements was to transition from flood irrigation to furrow (trench) irrigation which also increased spacing between sugar cane rows in the farm fields. The increased space produced triple benefits: (1) it allowed better soil aeration and gave plants more space to grow freely, producing cane plants of larger circumference and height and increased weight, with greater sugar content; (2) the cane plants required less water consumption per hectare of crop area; and (3) it allowed farmers to utilize the space between rows to cultivate additional crops inbetween sugarcane plants, there by enhancing the farm incomes.

Farmers participating in the program realized 19-34% (averaging 24%) enhanced sugar cane productivity and their farm revenues more than doubled.[104] Important to objectives of the project, the Better Management Practices enabled a 10-40% (average 17.4%) gain in water use efficiency in the sugar cane farms fed by the the Khanpur Minor Canal , and almost 70 million litres of saved water was routed to the Karula River to improve environmental flow conditions. These enhanced flows increased river flows during the low-flow season by 7%. With further adoption of Better Management Practices in the remaining sugarcane area it is expected that more water will be contributed to the Karula river.



CASE STUDY 5: SOUTH AFRICA

WWF-SOUTH AFRICA: BUILDING CAPACITY AND INSTITUTIONS FOR SUSTAINABLE GROUNDWATER MANAGEMENT IN CAPE TOWN

During 2015–2018, the cumulative effects of extreme drought and inadequate reduction in water demands left the city of Cape Town on the brink of becoming the first city in the world to run out of water. The city characterized this risk as Day Zero, a label that captured attention both locally and globally, as the crisis was widely publicized. Water conservation and demand management were implemented, with increasingly severe water restrictions for the largest users: agriculture and urban supply.

In response, many residents and businesses turned to alternate water sources such as recycled water—for use in gardens and toilets—and groundwater.[105] Many new wells were installed as surface water supplies became increasingly uncertain. This rapid rise in groundwater use raised new concerns: How many wells had been installed? How much groundwater was being used? Were extraction rates exceeding recharge? What impact might they have on ecosystems?

In early 2018, the city began implementing severe water restrictions in a bid to curb water usage and succeeded in reducing its daily water usage by more than half in March 2018. Strong rains starting in June 2018 began refilling the reservoirs. However, with many residents and businesses now using groundwater, the sustainability of this resource remains in question.

To address these groundwater questions, WWF-South Africa and AB InBev (the world's largest brewing company) joined forces in 2018 on a groundwater pilot study, mobilizing a citizen-science groundwater-monitoring program. Tackling groundwater issues together for two years gave the project partners good insight into the many gaps that were evident regarding groundwater in Cape Town.

The successful pilot study supported a strong argument for continued work. Funded by the Royal Danish Embassy, another two-year project ran from October 2020 until April 2022. This additional funding enabled a multifaceted and complex undertaking, which addressed gaps related to public education, citizen engagement, and knowledge of the status of groundwater at multiple levels simultaneously.

The effort included groundwater awareness work in schools (including the development of educational materials on groundwater, a poster competition, and a field excursion) and with faith groups (including the development of Sunday School materials, the training of Water Disciples within Green Anglicans, and field excursions), volunteer groundwater monitoring in residential and business areas, transparent groundwater information sharing via a newly developed, publicly accessible dashboard, improved city bulk water decision support systems that now consider groundwater as well as surface water, and a multiscale groundwater policy and governance review. The activities have all addressed crucial gaps that need to be addressed if groundwater is to gain the same resource status as surface water.

These multifaceted groundwater projects were the basis for the Table Mountain Water Source Partnership, launched in November 2021. The partnership has nine founding members from all levels of government, academic institutions, the private sector, and civil society. The partnership's vision statement reads as follows:

> *"Improving water security through monitoring and management, to ensure water resources can continue to support people and the ecosystem in and around the Table Mountain Strategic Water Source Area."*

The city of Cape Town has acknowledged and applauded the value of this partnership and the engaging discussions it has initiated, which have stimulated additional groundwater activities on-site and the exploration of the possible replication of similar groundwater activities and partnerships in other areas in South Africa.

Key learnings from the project include the following:

- → Groundwater partnerships, consisting of public, private, and community representation, need to co-create the partnership structure and functions to get to a point where managing and governing groundwater in a local setting becomes possible.
- → Groundwater users and managers can be governments, cities, and individual residents with a well in the backyard. Each level needs to be addressed in the journey to sustainable groundwater use and greater water resilience.
- → Drought events like Day Zero can be catalysts for lasting change in the use of water resources and the engagement of stakeholders around a common vision.

Next steps for the Table Mountain Water Source Partnership will include the following:

- → The partnership will continue and possibly expand the recently developed and launched dashboard and established groundwater-monitoring network, which are tangible partnership assets that must be maintained due to their long-term value.
- → A key focus will be groundwater quality, which affects all Cape Town residents, regardless of income, and for which there are significant data gaps. This will include the groundwater/surface water interface in Cape Town; the city is hoping to obtain Ramsar site status for its significant number of seasonal and permanent wetlands.
- → Awareness-raising should remain a key focus for the partnership, and new, innovative forms of education should remain a priority.
- → The partnership will encourage other projects to use the groundwater work its teams have completed as a blueprint or guideline for groundwater partnerships and projects in other areas of South Africa and beyond.

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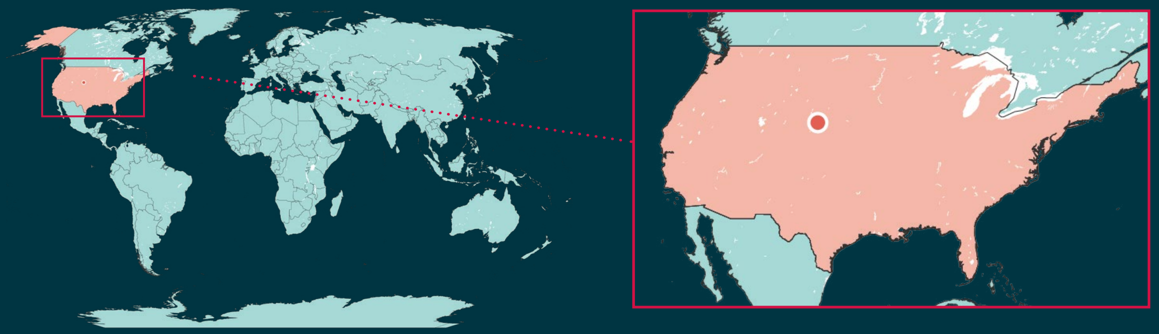

CASE STUDY 6: UNITED STATES (NEBRASKA)

STATEWIDE GROUNDWATER MANAGEMENT THROUGH LOCAL CONSERVATION DISTRICTS

About 93% of Nebraska groundwater withdrawals are used for irrigation.[106] The state has the largest number of irrigated acres in the US—over 8.6 million[107]—and is a significant agricultural producer to local and global economies. Eighty-nine percent of these acres are irrigated with groundwater. Thus, focusing on developing and improving policies aimed at preventing groundwater over-extraction and increasing long-term sustainable water management practices are of key importance.

Most groundwater used in Nebraska is pumped from the High Plains Aquifer (see Figure 2). Nearly all of the state's surface area (about 84%) is situated above the aquifer.[108] Nebraska covers about 166,000 square kilometers (36%) of the total aquifer, which accounts for about 60% of its water volume. Smaller aquifers that underlie Nebraska include the Dakota, Niobrara, and Paleovalley aquifers.[109,110] Hydrologic connectivity between groundwater and surface water is common across Nebraska; thus, integrating groundwater management with surface water planning has been an important focus for the past couple of decades.

The pumping of large amounts of groundwater for agricultural irrigation since the 1950s has affected groundwater levels as well as streamflow. Institutional changes have been made in Nebraska to address water sustainability issues, including the Nebraska Ground Water Management and Protection Act (1975), which transferred groundwater management authority to local agencies. These local agencies consist of 23 Natural Resources Districts (NRDs) governed by boards of directors who are elected locally and have the power to implement and enforce regulations. These districts follow the boundaries of Nebraska's major river basins.

To achieve groundwater sustainability goals, NRDs use different regulatory and incentive-based water management tools, which vary due to hydrogeological and climatic characteristics across Nebraska. In addition, many districts are legally accountable for the impacts of groundwater pumping on streamflow, as they are required to comply with rules identified in different interstate agreements.

Groundwater availability for irrigation is highly variable across Nebraska. Growers in the western portion of the state are especially prone to higher production uncertainties, given the much lower precipitation than in the eastern part of the state. Dry growing seasons increase irrigation demand, necessitating more flexible, localized solutions.

Fact sheets about studied water markets in different NRDs are available here:
https://waterforfood.nebraska.edu/our-work/research-and-policy/transferring-groundwater-in-the-high-plains

Groundwater management approaches used by many NRDs include moratoria on new groundwater wells and irrigated acres, as well as requirements to install irrigation flowmeters, provide groundwater use reports, and follow a groundwater allocation system, restricting pumping to a specified amount (e.g., 60 inches over a five-year period). The ability to bank unused allocation water for use in the next allocation period provides some flexibility in farmers' decision-making process. Additional production flexibility is supported by Nebraska's water law, which allows for separation between groundwater pumping rights and agricultural land ownership, supporting trading of groundwater rights.

Agricultural water markets can reduce production risks related to more intense and frequent water scarcity and drought events by allowing reallocation of water across time and space. Water markets in Nebraska have been active for several decades and are highly regulated by local governments through NRDs. The Daugherty Water for Food Global Institute at the University of Nebraska and the National Drought Mitigation Center studied multiple agricultural groundwater markets in Nebraska and found that water market structures varied highly across the state in order to address local needs.

Different environmental and conservation goals across Nebraska affect the complexities associated with a groundwater transfer approval process. Besides the statutory responsibility to ensure the long-term sustainability of water supply, some local governments have additional responsibilities as established in interstate compacts, settlements, and federal endangered species programs, which affect how they manage groundwater pumping as it relates to streamflow.

Another major difference is related to the type of groundwater transfer. In Nebraska, there are multiple forms of formal and informal groundwater transfers, all of which are highly regulated. Informal transfers usually do not account for impacts on streams.

Groundwater market transaction costs can also vary depending on rules specific to the area in Nebraska—they range from $0 to $10,000 per transfer. Other differences across Nebraska's agricultural groundwater markets include requirements or practices specific to transfer size and frequency, the role of the irrigation technology system used, and the terminology used to define these transfers.

Groundwater management approaches in Nebraska, including water markets, are unique and highly variable within the state due to localized priorities. They offer various lessons to other regions seeking to address groundwater sustainability concerns by putting stronger restrictions on groundwater management or implementing incentive-based management approaches. Learning from variability in Nebraska's groundwater transfer rules can help decision-makers as they try to implement similar tools in different regions.

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Cover photo description: Groundwater is pumped from a small tubewell to irrigate farmland in India.

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