Technical Report

Groundwater depletion

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Acknowledgements: We would like to thank Ambe Emmanuel Cheo, Zita Sebesvari and Jack O'Connor for their support in this research.

Risk Tipping Points

Interconnected Disaster Risks

2023

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Abbreviations

CBD	Convention on Biological Diversity
FAO	Food and Agriculture Organization of the United Nations
GRACE	Gravity Recovery and Climate Experiment
IGRAC	International Groundwater Resources Assessment Centre
PDS	Public Distribution System
SDG	Sustainable Development Goals
UN	United Nations
UN Water	United Nations Water
UNESCO	United Nations Educational, Scientific and Cultural Organization
USA	United States of America

1. Introduction

Groundwater is an essential freshwater resource, contained in *aquifers*, bodies of permeable rock and sediment, below Earth's surface. Around 30 per cent of the world's fresh water is stored as groundwater (IGRAC, 2021) and occasionally brought to the surface through springs, lakes or streams, or is extracted from wells drilled into the aquifer. Over 2 billion people rely on groundwater as an essential supply of drinking water (Kundzewicz and Döll, 2009), but around 70 per cent of all groundwater withdrawals are used for agricultural purposes (UN Water, 2022). These activities extract water from the aquifer, lowering the water table, while rainwater, snowmelt, riverine contributions or other surface water can recharge some aquifers, raising the water table (Hartmann, 2022).

This balance between extraction and recharge is critical to maintain stable water levels and ensure a reliable supply for irrigation and drinking water. However, research has shown that 21 out of the 37 largest global aquifer systems have negative subsurface trends, as groundwater resources are being depleted faster than they can be recharged (Richey and others, 2015). Groundwater depletion can be defined as the "prolonged (multi-annual) withdrawal of groundwater from an aquifer in quantities exceeding average annual replenishment, leading to a persistent decline in groundwater levels and reduction of groundwater volumes" (Bierkens and Wada, 2019). Accelerated extraction rates, particularly from agricultural intensification, are putting groundwater resources and the systems that depend on them at risk.

A dog hangs around an abandoned farmhouse in February 2014 near Bakersfield, California. The area experienced its driest year on record, dating back 119 years and possibly the worst in the past 500 years.
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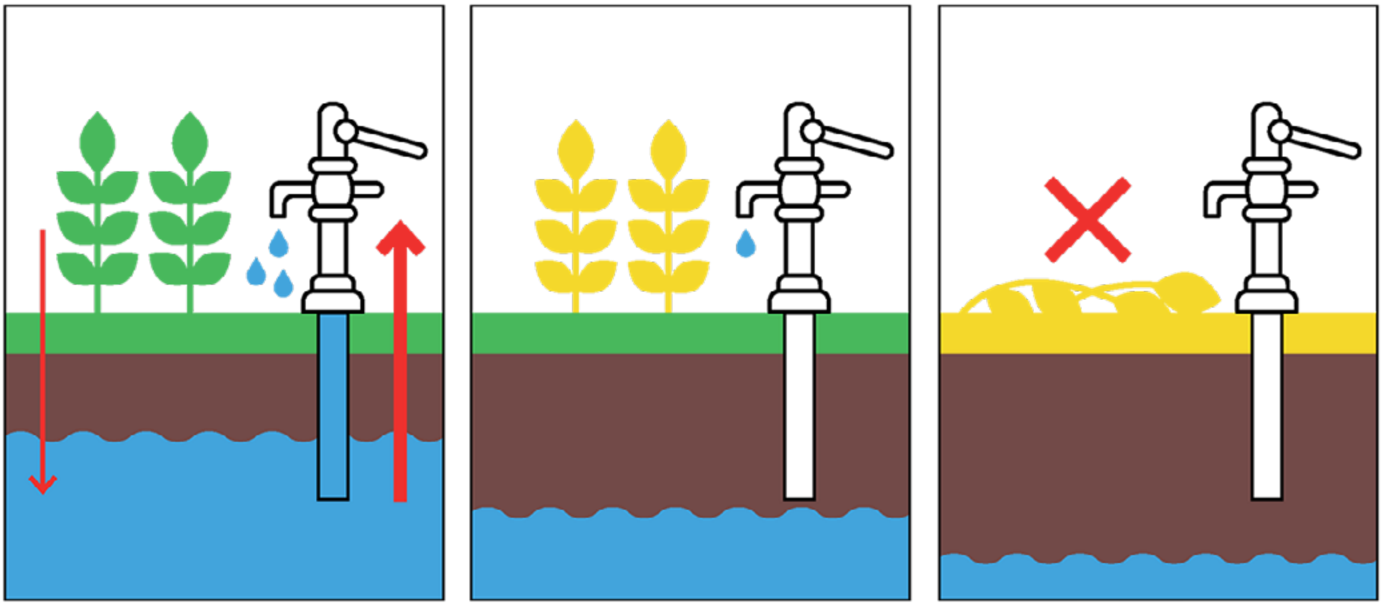
2. Risk tipping point

As groundwater is extracted faster than it can be replenished, the water table drops further and further away from the Earth's surface. This can become problematic, as wells are drilled or dug only to a certain depth. Eventually, people extracting groundwater from wells will soon face a risk tipping point when the water table in a given aquifer drops consistently below the well depth. At this point, the water will be inaccessible from the existing well infrastructure. This increases the risk that crops will be unable to be irrigated, forcing farmers to rely on other, often unreliable, sources of water. This also brings risks of the failure of food production systems that are reliant on groundwater for irrigation, with far-reaching consequences for consumers, people's livelihoods and nutrition and ecosystems (see Chapter 4).



1. Increasing risk = More groundwater is extracted than is able to be recharged

2. Tipping point = Water table drops consistently below well depth

3. Tipped = Access to groundwater is unavailable, increasing the risk of crop failure

Figure 1: The groundwater risk tipping point is reached when the water table in a given aquifer drops consistently below the well depth. Access to groundwater will become problematic, increasing the risk that farmers will be unable to irrigate their crops

Groundwater depletion rates worldwide have accelerated since the mid-twentieth century, to the extent that groundwater is a non-trivial contributor to sea level rise (Aeschbach-Hertig and Gleeson, 2012). The excessive pumping of groundwater has also caused the Earth's axis to tilt 4.36 centimetres per year (Castelvecchi, 2023). The regions where groundwater depletion is most severe include parts of India, north-eastern China, western United States, Mexico, Iran, Saudi Arabia and parts of Northern Africa (Aeschbach-Hertig and Gleeson, 2012). Some of these places are already unable to reach this resource and have had to adjust to the consequences of groundwater depletion.

This risk tipping point can be crossed by different people and places at different times. For example, the High Plains aquifer in the USA is one of the world's largest aquifers, but the great overreliance and rampant groundwater pumping led to rapidly falling water levels in some parts of the aquifer. In fact, the continued unsustainable groundwater extraction is depleting the High Plains aquifer and around 40 per cent of the aquifer's area will not support irrigation by the year 2100 (Haacker and others, 2016). This will have negative consequences for not only national territory but also for the countries far away that import U.S. crops. However, the degree of depletion is not the same throughout the aquifer (Aeschbach-Hertig and Gleeson, 2012), as some regions, such as the northern section of the aquifer, occasionally experience increasing water levels.

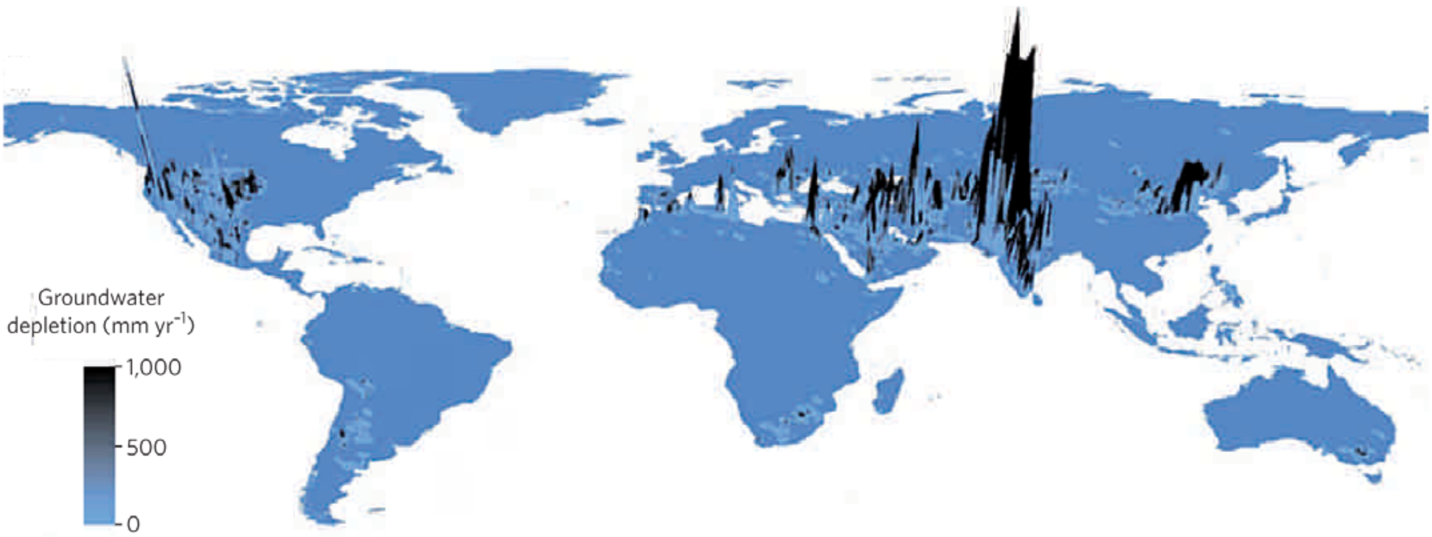


Figure 2: Estimate of the global distribution of groundwater depletion is remapped as three-dimensional topography to show "mountains of groundwater depletion" especially in the United States, Mexico, Saudi Arabia, Pakistan, India and China. The colour scale is based on the concept of blue water (renewable surface water and groundwater) and dark blue water (non-renewable groundwater). Taken from Aeschbach-Hertig and Gleeson, 2012.

Nonetheless, this risk tipping point does not necessarily represent a final, irreversible point of no return in all cases. For example, it is not impossible for aquifers to sufficiently recharge and to be reachable again by existing infrastructure. For some shallow aquifers, it may take less than a decade for them to recharge naturally, while for others with different geological characteristics it may take thousands of years (Little, 2009; Schreiner-McGraw and Ajami, 2021). However, past the risk tipping point only some people may have the capacity to cope by drilling deeper wells or supplement irrigation with other water sources, or to adapt by pursuing other livelihood options, but others will not.

3. How did we get here?

3.1 Drivers

3.1.1 Risk-intensifying land use

Agricultural intensification is a major factor pushing us towards a groundwater depletion risk tipping point (Bierkens and Wada, 2019; Rodella and others, 2023). Groundwater irrigation sustains the production of approximately 40 per cent of the world's crops, including a large portion of staple crops like rice and wheat (Jain and others, 2021). Access to groundwater has driven the expansion of irrigated agricultural land worldwide. The twentieth century alone has seen a dramatic increase, from 63 million hectares in 1900 to 306 million hectares in 2005 (Siebert and others, 2015), as well as the expansion of irrigated land to even semi-arid areas with limited precipitation and surface water (Bierkens and Wada, 2019). Saudi Arabia, for instance, has no permanent lakes or rivers and receives little rainfall. However, the country sits atop one of the world's largest aquifer systems and was able to use its groundwater resources to grow wheat in the desert. In an attempt to make the country self-sufficient, the government provided generous subsidies to extract water in large quantities, using central-pivot irrigation systems to grow wheat (Al Felou, 2022). By the mid-1990s, farmers were pumping around 19 trillion litres per year, and Saudi Arabia became the world's sixth-largest wheat exporter (Halverson, 2015). This vast overextraction is estimated to have depleted over 80 per cent of the aquifer (Novo, 2019).

Satellite imagery of central pivot irrigation in the desert of Saudi Arabia. A time-lapse is available here:
https://www.esa.int/ESA_Multimedia/Videos/2017/10/Sustenance_from_the_sands
©USGS / contains modified Coperncius Sentinel data (2016), processed by ESA.

As another example, in the 1960s, India experienced food shortages and famine that led to the promotion of crop intensification. The government's national food procurement and distribution system, known as the Public Distribution System (PDS) ensures lower-income households' access to food, but it also influences land-use patterns. Since government purchases guarantee a set income, farmers' decisions on which crops to plant have been influenced by the PDS's demand, motivating some farmers in locations with inadequate climatic and soil conditions to grow, for example, water-intensive crops such as rice (Devineni and others, 2022), To keep costs to a minimum, the PDS purchases most crops from just a few provinces, such as Haryana and Punjab, where productivity rates of wheat and rice are the highest (Ambast and others, 2006). Together these provinces produce around 50 per cent of the country's rice supply and 85 per cent of its wheat stocks (Shiao and others, 2015). However, particularly in the province of Punjab, where 98.9 per cent of cropland is irrigated by ground and surface water (The Times of India, 2022), 78 per cent of wells are considered overexploited (Ministry of Jal Shakti, 2021) and the north-western region as a whole is predicted to experience critically low groundwater availability as soon as 2025 (Jain and others, 2021).

3.1.2 Insufficient future planning

In some aquifers, groundwater is much like fossil fuels; once the resource is used up, getting it back can be almost impossible. As such, planning and managing should be done in a way that is mindful of the limited nature of the resource, yet this is often not the case. Especially in arid areas or when rains fail, groundwater is essential. However, the outdated notion that groundwater is inexhaustible has caused overreliance, leading to depletion, and insufficient planning for the risks of running out of groundwater. Groundwater is generally managed in a reactive rather than proactive way, where undesired trends are corrected after they have occurred rather than prevented from happening (Margat and Van der Gun, 2013). As previously mentioned, Saudi Arabia, for example, turned the desert into a major wheat production area in the span of about a decade, using the money and water that was available to them. However, this could only last until either the water or the money ran out (Elhadj, 2004), this case being the water running out. The aquifer had been built up over tens of thousands of years and the area did not get nearly enough rainfall to replace the withdrawals (Plumer, 2015). Agricultural output declined, with less than half the amount of farmland in 2015 than there was in the 1990s (Plumer, 2015). The country only began taking contingency measures once the severe impact its production model had on its groundwater stores became noticeable. Indeed, the Saudi government announced a halt to domestic wheat production in an attempt to conserve the remaining water (Halverson, 2015), and also established a public fund to support investments in other nations to grow wheat there, including Argentina, the USA, Sudan, Australia, Brazil, Egypt and Ukraine (Al Felou, 2022) (see chapter 3.2.1). In 2017, the Saudi government did loosen some restrictions to allow more wheat production in small land holdings under 50 hectares (Al Felou, 2022) – likely motivated by a desire to reduce the country's reliance on imports from other countries.

3.1.3 Lack of information

Groundwater, unlike surface water, is hidden underground, limiting human ability to foresee the changes that happen in these reservoirs. Most people have only a vague notion of how groundwater and aquifers work, which could lead to mismanagement (Margat and Van der Gun, 2013). In general terms, there tends to be little monitoring and few long-term observations of groundwater withdrawals, while recharge rates tend to be an estimate rather than consistently measured data (Vasco and others, 2019; Liu and others, 2022). Groundwater monitoring is usually the responsibility of public institutions and in many places, the cost of developing, operating and maintaining a monitoring network is a constraining factor (UN Water, 2022). In other cases, the monitoring of groundwater withdrawals is not required by public authorities (Vasco and others, 2019). Where there are in situ observations, they tend to be scattered and cover only a short period of time, limiting the development of predictive and large-scale models that can support management decisions (Liu and others, 2022). This lack of information means that often we do not know how much groundwater is actually available, which favours the practice of overextraction since it makes sustainable water management efforts more difficult to develop (Vasco and others, 2019).

3.1.4 Lack of regulations/enforcement

Regulations, either formal or informal, of a common-pool resource like groundwater should ideally prevent wasteful use and the complete depletion of the resource. However, government policies, or a lack thereof, can encourage groundwater depletion. In some cases, laws have allowed landowners to extract groundwater without restrains (Burchi and Nanni, 2003). Traditionally and still in many countries, groundwater rights are privately owned, and this has contributed to groundwater depletion (Burchi and Nanni, 2003) since the reach of certain regulations is somewhat limited.

For example, in the High Plains aquifer in midwestern USA, water-use rights are determined based on the doctrine of prior appropriation otherwise known as “first in time, first in right” (Sanderson and Hughes, 2019) along with the doctrine of beneficial use. The doctrine of prior appropriation grants rights based on a priority date, in which the older the claim, the more secure the right is (Hockaday and Ormerod, 2020). It means that in the case of shortages or conflicts, the more senior water rights holder is prioritized over the junior, giving the senior holders the right to obtain their approved allocated water in full, even at the expense of the junior holder (Aiken, 1988).

A tractor kicks up dust as it plows a dry field in May 2021, California, USA. As the state enters an extreme drought emergency, water is starting to become scarce in California’s Central Valley, one of the most productive agricultural regions in the world.
© Justin Sullivan / Getty Images / AFP

Appropriative water rights are also based in the doctrine of beneficial use (Aiken, 1988; Hockaday and Ormerod, 2020), meaning that each water right is designated for one use, such as irrigation, municipal, industrial or other, and water allocation is approved in an amount sufficient to the activity. Even though the principle of beneficial use is intended to promote the rational use of water and to limit speculative holding of water rights (Aiken, 1988; Richmond and others, 2021), in practice, it results in inefficient and wasteful use (Aiken, 1988). When farmers are approved an amount of water but consistently underutilize their full allocation, their water rights may be curtailed. This policy can incentivize inefficient irrigation strategies by encouraging farmers to use all water that is allocated, independent of the current need, leading to overuse and depletion (Aiken, 1988). Also, in the event water holders stop using their allocated water altogether, they would lose their water right. The intention of this is to make more water rights available for junior users. Nonetheless, because holding a right over time gives the water holder more leverage, it can incentivize farmers to continue their activities and make the most of the available resource, contributing to groundwater depletion.

3.2 Root causes

3.2.1 Prioritizing profits

Groundwater is a type of common-pool resource, one with a relatively finite supply that is not owned by any one entity but rather shared by many. As discussed in the theory of "The Tragedy of the Commons," these resources are particularly susceptible to overexploitation and degradation (Hardin, 1968). Individuals are free to take advantage of those resources for short-term gains that undermine the long-term sustainability of the resource for everyone since the costs of degradation or depletion are externalized and distributed among all users (Clancy, 1998). Aquifers, for example, have relatively limited supply, and users are driven by a sense of competition to optimize individual benefits (Müller and others, 2017), motivated by the belief that others will not act in the best interest of the collective or without a long-term perspective in mind, which ultimately leads to a depletion of the aquifer over time.

To a certain extent, the wasteful use of groundwater is rooted in the economy of the agricultural sector. Many farmers around the world make just enough to make ends meet, including farmers in the USA. To compensate for their losses, farmers in the USA tend to expand their cultivated land, taking out further bank loans or collecting the payouts of federal farm subsidies or crop insurance. However, research suggests that these subsidies and payouts only serve to further the problem. In 2019, for instance, corn had a near-record year of production and farm incomes increased by almost 6 per cent (Griggs and others, 2022). However, corn market prices were too low to cover the cost of growing it, so the difference was made up by federal subsidies. Many crops have similar low market prices that are unable to cover the expense of production, and are similarly covered by subsidies or insurance. Many farmers purchase more land or expensive equipment with these payouts in an attempt to increase their profits, but often growing more food only floods the market further, reducing crop prices and incomes (Griggs and others, 2022). As such, measures to increase farmers' profits often do not necessarily increase farmers' incomes, but often traps them in a cycle of debt and glut commodity markets that end up draining the aquifers (Bessire, 2021).

3.2.2 Global demand pressures

A strong relationship between groundwater and international food supply chains is also driving groundwater depletion. Many of the products grown in countries that overdraft their groundwater resources are sold and consumed in places far away. The water required to produce a product is known as “virtual water” (D’Odorico and others, 2019). In this case, though the groundwater is not physically exported, it is traded in the form of virtual water used for irrigating crops. About 11 per cent of depleted groundwater is embedded in international crop trade in the form of virtual water, of which Pakistan, the USA, and India export around two-thirds (Dalin and others, 2017). Pakistan, for instance, has the highest water consumption per unit of GDP (Wattoo and Mehmood, 2022) since they export around 30 per cent of the world’s groundwater-depleting crops (Dalin and others, 2017).

The demand for groundwater-depleting crops puts both the exporting and importing countries at risk. The demand for food from abroad drives increasing groundwater depletion locally, as farmers are incentivized to grow and sell for an international market. This also may bring international companies to highly productive regions, such as the USA. Large, multinational companies purchase land in places like the High Plains, often displacing family farms. These corporations and shell companies become absentee landowners, paying virtually nothing for the groundwater they use except the cost of pumping and exporting those profits away from the place they were generated. This leaves those who are left to deal with the negative consequences of a depleted aquifer (Bessire, 2021) but none of the benefits that would normally be provided by a business reinvesting in the region. This situation also puts importing countries at risk, as they may be relying on crops that come from highly stressed aquifers (see Chapter 4.3). The USA exports 42 per cent of its crops grown from depleted groundwater, mostly corn, to other places like Mexico, China and Japan (Dalin and others, 2017), but if the groundwater is depleted, then these countries will no longer be able to rely on the US as a source of food.

Hereford cattle roam the dirt-brown fields of the outskirts of Delano, in California’s Central Valley in February 2014. At this time of the year the fields would normally be covered in lush green grass, but the western US states’ worst drought in decades reduced the land to a parched moonscape.
© Frederic J. Brown / AFP Photo

3.2.3 Insufficient risk management

Groundwater tends to be perceived as a reliable and safe source of water, available independent of seasonal or climatic changes. Reaching it is not easy though; it comes at a cost for the farmers who have to pay for the equipment to dig a well and for the running cost of the electricity required to bring water out to the surface. To support farmers and reduce their running costs, some countries subsidize the energy cost for water pumping. While government subsidies of this nature are meant to ease affordability and accessibility to groundwater, they also increase the probability of overextracting this valuable resource, and decrease any incentive to diversify irrigation methods. In the case of India, energy subsidies, together with other factors, have shown to drive groundwater depletion (Pandey and others, 2022; Devineni and others, 2022). In the aftermath of the previously mentioned food shortages, a series of government incentives aimed to increase the country's food supply, including a subsidy for electricity to pump water for irrigation (Devineni and others, 2022), have contributed to the increase in the number of wells across India since the 1960s (Jain and others, 2021). Increased access to groundwater has allowed farmers to improve cropping intensity, as well as expand the number of cropping seasons in a year, by extending production into the predominantly dry winter and summer months (Jain and others, 2021). Following challenges to meter, bill, and collect payments in the use of electricity for groundwater pumping, most State Electricity Boards moved to flat tariffs in 1970, which reduced the cost of pumping for the farmers to virtually net zero (Pandey and others, 2022). While the use of groundwater and production rates has grown over the years, the development of other irrigation alternatives like canals has lagged due to bureaucratic and design failures (Pandey and others, 2022). Thus, though these programmes are well-intentioned, they increase the pressure and reliance on rapidly depleting groundwater resources, without setting up contingency plans in the event a risk tipping point is reached.

A man stands behind a borewell drilling machine in a crop field in Punjab, India, in May 2023. © Polina Schapova / UNU-EHS

3.2.4 Insufficient cooperation

Water resources extend beyond administrative borders, posing a management challenge. Aquifers are no exception and represent a greater challenge because their water is hidden underground, and those that cross over national borders are particularly complicated cases. For instance, international law on shared groundwater is in its infancy. What exists on this front are draft articles on a “law of transboundary aquifers” issued in 2013 by the United Nations General Assembly resolution 68/118 that serve as guidelines for bilateral or regional agreements but have no legal power (Müller and others, 2017). Additionally, cooperation on transboundary aquifers was found to be lagging in comparison to surface water, though improvements have been observed in the 2021 SDG agenda compared with the report in 2018 (UN and UNESCO, 2018; UN Water, 2021). While above-ground transboundary water resources receive comparatively more attention, it should be noted that the secondary importance given to the topic of groundwater in the international research and policy agenda puts groundwater resources at risk, and it is likely shaped by the lack of understanding of the importance of groundwater for food and water security.

The reality is that in some areas of the world, particularly in semi-arid and arid regions, countries depend on groundwater from transboundary aquifers. This is the case for Pakistan and India, as well as for countries in the Arabian Peninsula. Pakistan and India have a history of tension over the use of the waters of the Indus River basin. To ease the situation and avoid violent conflicts, the Indus Water Treaty was signed in 1960. However, groundwater is greatly overlooked in the treaty even though it is crucial for the economy and food security of both countries (Jayaram, 2016). Another important transboundary aquifer is the one shared by Jordan and Saudi Arabia. Jordan holds only a small section of the Disi aquifer, but it is critical for alleviating the country’s extreme water scarcity. It is used to supply drinking water to the capital city of Amman, as well as to the coastal city of Aqaba, while also supporting irrigated agriculture in the surroundings of Aqaba. This aquifer is the same one that Saudi Arabia heavily used to source the water for the country’s extensive wheat production at the end of the twentieth century, and a potential expansion of Saudi Arabia’s current rates of abstraction is regarded as a major risk to Jordan’s long-term reliability on the Disi aquifer (Müller and others, 2017).

3.3 Influences

We live in an interconnected world, where reaching one risk tipping point influences others. Groundwater resources support various systems on the planet, and as we deplete them, we put those other systems at risk as well. For example, groundwater resources support underground ecosystems and species that have specialized to live in naturally narrow and fragmented conditions. Declining levels in the water table strand the distribution of stygofauna and test the survival of some taxa (Stumpp and Hose, 2013). There is also evidence indicating that endemic species to the Edwards–Trinity aquifer system, located in west-central Texas, are highly vulnerable to extinction within the next century as a result of groundwater depletion and increased air temperature (Devitt and others, 2019). Particularly, the Eurycea salamanders are experiencing habitat loss at the surface and subsurface, as water tables decline and spring flows have reduced (Devitt and others, 2019) in response to the overextraction of groundwater. This has resulted in declines of individual salamander populations and local extinctions, which could imply secondary and cascading extinctions, risking the loss of ecological interactions among dependent species and potentially triggering a chain reaction through the entire ecosystem, influencing the **Accelerating extinctions tipping** point.

Groundwater depletion can influence the occurrence of Unbearable heat. Groundwater near the land surface has a cooling effect on land and the atmosphere, but its moderating effect during a heatwave decreases as the groundwater table falls (Mu and others, 2022). Also, as groundwater is extracted to the surface where it can more easily evaporate, it increases the surrounding humidity in the air and contributes to increasing wet-bulb temperatures (Ambika and Mishra, 2022).

Groundwater helps maintain minimum water levels in rivers and other water bodies like wetlands. Depleting groundwater levels could interact with the Mountain glaciers melting risk tipping point, and significantly reduce river flow in basins where these two water components are significant, especially during dry periods. Additionally, as Mountain glaciers melt away, their contribution to an aquifer's recharge diminishes. At the same time, the risk tipping point of Space debris increases the risk of damaging the satellite infrastructure that we rely on back on Earth to monitor complex and hidden systems to the naked eye, such as aquifers.

4. Where are we headed? Current and future impacts

4.1 Livelihood loss

Groundwater accounts for 43 per cent of all water used for agriculture (Rodella and others, 2023) and reaching the risk tipping point represents a loss of livelihoods. Losing access to groundwater is likely to reduce crop yields, and thus also impacts both farming livelihoods and food security. Groundwater depletion has caused rampant reductions in crop yields in the USA, where several counties have experienced the lowest corn yields since the 1960s. One county in Kansas, for example, experienced yields of just 70 bushels per acre in 2022 compared to 175 in the late 1990s (Budryk, 2023).

Agriculture provides livelihoods for 2.5 billion people worldwide and is the largest source of income and jobs for rural households (CBD, 2018). In India, agriculture and its associated sectors account for the largest source of livelihoods (FAO, 1999), representing approximately 8 per cent of the world's population (Jain and others, 2021). Research shows that marginalized farmers are generally more likely to experience negative consequences when unable to reach groundwater, with empirical evidence from India showing only a small percentage of farmers were able to sustain agricultural production in their plots in such cases (Rodella and others, 2023). In other cases, a dynamic of "chasing down the water table" by digging deeper wells was observed. This practice leads to the unprofitability of groundwater-dependent activities, due to high costs and lower groundwater yields, eventually leading to a full abandonment of these activities (Rodella and others, 2023).

A farmer sifts through arid topsoil under a ruined crop on the family farm in August 2012 in Logan, Kansas.
© John Moore / Getty Images / AFP

4.2 Migration/displacement

Migration or displacement can occur because of groundwater depletion, primarily as people lose their livelihoods due to the impacts on agriculture. For example, evidence from India indicates that the abandonment of groundwater-dependent activities as a result of well failure has led to male labour migration to urban areas (Rodella and others, 2023; Fishman and others, 2013). In fact, one study estimated that for every 30 metres increase in the depth of groundwater wells in Gujarat, India, there was a 2.5 per cent increase in the likelihood that a household had at least one migrant son (Fishman and others, 2013). Most of the migration occurred from the dominant, land-owning caste, with less evidence of migration from agriculture within villages (Fishman and others, 2013) – perhaps due to education or financial barriers keeping certain farmers tied to agricultural livelihoods, even in the face of scarcity.

Additionally, the Sahel and Sahara regions in Africa rely on groundwater as the only source of water, often only found at depths greater than 500 metres. Since people's lives depend on the availability and storage of fresh water, continued groundwater depletion is exacerbating existing water shortages, leading to crop failure and water-driven conflicts (Xu and Famiglietti, 2023). There is evidence of migration driven by water shortage and food security issues in places such as Burkina Faso, Sudan, Mali, Senegal and Mauritania (Xu and Famiglietti, 2023).

4.3 Loss of safety

Depleting groundwater resources also represent the loss of a safety mechanism. Groundwater is widely considered a reliable water source that compensates for scarce surface water availability and little or unreliable rain (Taylor and Shamsudduha, 2022). For example, the groundwater depletion in Kansas, USA has caused many farmers to switch from groundwater irrigation to dryland farming that relies entirely on rainfall. However, the amount of rainfall the area gets is not enough to compensate for the loss of groundwater for irrigation (Budryk, 2023), and thus, farmers must supplement this strategy with other water-saving techniques (see chapter 5.2). Losing the security groundwater provides, relative to surface water resources, is a risk for both current and future generations. Depleting our groundwater resources now deprives future generations of the benefit and the safety past generations have enjoyed. Until now, groundwater has been a coping strategy for droughts, and it will likely become more important as the probability of drought events increases in the face of climate change (Dalin, 2020).

4.4 Food and water insecurity

The risk tipping point of inaccessibility to groundwater impacts food and water security. Groundwater is vital for food production as it is used for irrigated agriculture, cattle farming and other activities like food processing. For example, the High Plains aquifer in the United States supplies one-third of all groundwater for irrigation used in the country (Dennehy and others, 2002) and supports over $35 billion worth of crops such as wheat and soy (Basso and others, 2013), accounting for as much of 40 per cent of the vegetables, nuts and fruits consumed in the USA, more than 40 per cent of the nation's beef production, and nearly 20 per cent of the world's grain crops (Bessire, 2021). These food sources would all be reduced, or disappear entirely, if access to groundwater is lost. Additionally, groundwater depletion will represent a loss of security for nations that rely on staple crops imported from other countries suffering from groundwater depletion. For example, as Saudi Arabia has depleted much of its groundwater resources, the country relies on crops imported from other countries to meet up to 75 per cent of food consumption needs (Halverson, 2015; Mousa, 2022). In fact, the vast majority of the world's population lives in countries that source nearly all of their staple crops from trade partners that deplete their groundwater to produce them (Dalin and others, 2017).

Additionally, groundwater is an important source of water for domestic use, representing 49 per cent of all withdrawals for this use globally (Rodella and others, 2023). In the Middle East, South Asia, and Central Asia over 80 per cent of large cities rely on groundwater as their main source (Rodella and others, 2023). In California, USA, groundwater depletion could affect 9,000 domestic private wells and around 1,000 public supply wells (Bostic and others, 2023). In India, over 85 per cent of rural drinking water is sourced from groundwater, and its depletion is already threating water security in rural areas.

4.5 Ecosystem damage and biodiversity loss

As mentioned before, groundwater depletion can affect different species living in underground aquifers, increasing the likelihood of **Accelerating extinctions** (Stumpp and Hose, 2013; Devitt and others, 2019) (see **Chapter 3.3**). Groundwater depletion can impact ecosystem functions and services beyond the aquifer itself: ecosystems on the surface, rivers and lakes are further threatened (Chakraborty and others, 2023). For example, shallow groundwater sustains river baseflow and root-zone soil water in the absence of rain (Fan and others, 2013). Consequently, when groundwater supply is compromised, these fragile areas and their biodiversity are more susceptible during extreme dry periods (Boulton and Hancock, 2006).

Furthermore, the impacts of groundwater depletion can directly affect wetlands' health to the point of degradation. This depletion affects the provisioning of services that are key for dependent communities. As with some cases in Spain, unsustainable groundwater withdrawals have been pointed out as the main culprit for the degradation of wetlands (Llamas, 1989; Esteban and others, 2021; Acreman and others, 2022).

5. The future we want to create

To assess solutions for avoiding risk tipping points, we must consider these key questions: Does the solution attempt to prevent negative system changes or target adaptation to them? Does the solution work within the current system or drive a fundamental reimagining of the system? Answering these questions is critical for understanding how different actions advance risk reduction goals and yield varied outcomes, including potential consequences and trade-offs. To navigate this, we have developed the ADAT2 framework, which classifies solutions into four categories: Adapt-Delay, Adapt-Transform, Avoid-Delay, and Avoid-Transform — see the main report for details.

5.1 Avoid

Avoid actions alter the system to prevent crossing risk tipping points. Avoiding crossing a groundwater depletion risk tipping point requires a careful act of balancing groundwater withdrawals to aquifers' recharge rates. Notably, this does not mean we must stop using groundwater, but that we be mindful of the interconnected processes and systems reliant on this resource and ensure it is used sustainably. Thus, we need solutions that avoid the wasteful use of groundwater while also facilitating better recharge strategies.

Some solutions can be as practical as fixing leakages in distribution systems, particularly those used for irrigation where the pipes are usually visible and leakages are comparatively easier to stop than subsurface systems.

Reducing the wasteful use of water can also be promoted with more efficient irrigation practices. Drip irrigation, for example, uses pipes and devices that act as drippers to deliver water directly to the soil near a plant's roots and in small amounts. When compared to other types of irrigation like overhead sprinklers, drip irrigation is more efficient at delivering water directly to the crops while wasting less water and hence is a commonly proposed alternative to save water (van der Kooij and others, 2013).

Alongside technologies like drip irrigation, improved irrigation scheduling can also contribute to reducing the amount of water applied to crops. Such alternatives include, for example, evapotranspiration-based scheduling which can be done by consulting daily report services or by installing devices and controllers within the farm. Another option is soil moisture sensors to estimate the root-zone water availability. Farmers in Kansas and Texas who are part of the Ogallala Aquifer Program, meant to improve water management in the High Plains Aquifer, have seen a reduction of up to 15 per cent in irrigation water application during the last 10 years when using evapotranspiration-based irrigation scheduling (Ajaz and others, 2020).

Increased irrigation water efficiency is generally a good practice but might come with a paradox. It has been observed that programmes meant to reduce water withdrawals may also bring outcomes like increasing irrigation area, as increased efficiency can cover more area with the same amount of water that was previously used, or can induce greater extractions, worsening depletion rates (Lankford, 2023). However, some also argue the irrigation efficiency paradox is a miscalculation and inappropriately described from a hydrological perspective (Lankford, 2023). Another paradox might be emerging with the increased use of solar power to tap groundwater in places that have traditionally been out of reach due to high energy prices. Evidence suggests that solar-powered irrigation may lead to more groundwater drawdown, both in the long and the short term (Rodella and others, 2023). Attention must be brought to these issues, as well-intended policies might turn out to cause long-term harm, especially when groundwater volume changes are difficult to observe and monitor, and are poorly regulated.

In addition to improving irrigation efficiency to avoid wasteful use and conserve as much groundwater as possible, we can also act to boost the available groundwater resources by facilitating aquifer recharge. For example, interventions, such as restoring wetlands that enhances water infiltration to the subsurface, can enhance natural aquifer recharge while also protecting an endangered ecosystem (Conlisk and others, 2022). Other ways to enhance natural infiltration include collecting rain and stormwater that can be diverted to well-draining soils, small-scale river damming or artificial streams and ponds (Luxem, 2017). All these options can contribute to subsurface water infiltration, while they also can be used directly for irrigation.

Use of drip irrigation in a young apple orchard.
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An eco-friendly check dam is used to harvest rainwater for irrigation in Rajasthan, India. © Govindasamy Agoramoorthy / Shutterstock

These options are better suited for shallow aquifers which have faster recharge rates, as not all aquifers are the same, and some take longer than others to recharge. Shallow aquifers may recharge within a decade and for others it can take thousands of years (Little, 2009; Schreiner-McGraw and Ajami, 2021). In fact, some aquifers have not seen the addition of a drop of water since the beginning of the Holocene – approximately 12,000 years before the present (Bierkens and Wada, 2019). For confined aquifers, located beneath a layer of material that is impermeable and prevents water from penetrating through the surface, another recharge option, known as deep injection, is possible. Deep injection consists of putting water directly into the aquifer using wells and sourcing it from rainwater, stormwater or treated wastewater (Luxem, 2017). Importantly, recharge options can be helpful to address groundwater depletion either before or after crossing the risk tipping point, but they become critical closer to that point of inflection.

Additionally, enhancing groundwater monitoring can help inform and better water management practices. Satellite observations, for example, have often been used to overcome the information gap and to study wider land areas. Gravity Recovery and Climate Experiment (GRACE) measures changes in groundwater storage masses to create a more comprehensive picture of groundwater availability (Hicks, 2007), (see the **Space debris** Technical Report for more details).

From an individual perspective, chasing the water table down by digging deeper wells could be considered a temporary solution to address groundwater depletion. However, from a long-term perspective and considering that groundwater is a shared resource, it would contribute to the groundwater depletion risk tipping point. Digging deeper wells could be feasible for farmers with the available capital resources for a costly investment but for less wealthy farmers this is not possible (Jasechko and Perrone, 2021). From a common-pool perspective, one farmer's overextraction of groundwater from a depleting aquifer has consequences on the others and deepens the risk of inaccessibility to the resource. Even if the aquifer were to recharge within a reasonable time, the farmers profiting from a depleting aquifer would be contributing to bringing the water table further down, not allowing for the possibility of the water table to recharge to a more easily accessible level. Additionally, in some cases, the characteristics of the aquifer make it unfeasible, including, in some instances, very low yields at deeper depths (Jasechko and Perrone, 2021)

5.2 Adapt

Adapt actions reduce exposure to post-tipping point impacts and prepare for sustainable living within the new system. Adapting to groundwater depletion can be done in several ways, but the extent to which these are implemented in a way that promotes a more sustainable living, is a matter of choice. Past the risk tipping point, people will have to adapt to less water availability with an array of impacts to their lives. For instance, utilizing alternative water sources to groundwater for irrigation can relieve the pressure on aquifers. This, if applied simultaneously with other solutions, could potentially contribute to the gradual process of avoiding crossing the risk tipping point, but could also help people to adapt to groundwater disappearance.

Treated grey, black and desalinized water can also be used for crop irrigation and non-potable domestic uses. Grey water, for example, is used water that comes from sinks, washing machines, bathtubs and showers and represents a varying but significant portion of around 70 per cent of household outputs (Oteng-Peprah and others, 2018). Grey water for irrigation requires little treatment and is a relatively inexpensive supplementary source of water for irrigation (Oteng-Peprah and others, 2018). Black wastewater, on the other hand, contains toxic chemicals or excrement and requires specialized treatment, and is thus very costly. Similarly, desalinating water with varying salt content is also an expensive alternative usually afforded only by richer nations (Qadir and Scott, 2023). Additionally, the desalination process is energy intensive and, if fuelled by a non-renewable source, further contributes to greenhouse gas emissions (Panagopoulos and Haralambous, 2020). Also, some outputs of the process are toxic, and if handled inappropriately, can cause environmental harm. Overall, attention should be drawn to the potential negative consequences of using treated wastewater or desalinized water for irrigation as it could cause nutrient soil imbalances and contamination, as well as potential emergence of exposure to pathogens and other contaminants (Qadir and Scott, 2023).

Other alternatives include improved agricultural practices, including farming techniques suited for arid and semi-arid places. For instance, in the farming community of Garden City, Kansas, a growing group of farmers have chosen to develop a “dryland farming” system that reduces or even eliminates groundwater use (Little, 2009). This group of farmers is a minority among the neighbouring farmlands as a majority have continued and even increased the number of wells despite being aware that parts of the High Plains aquifers are in serious danger of depletion. Dryland farming is a special case of rain-fed agriculture practiced in arid and semi-arid regions in which farming practices emphasize water conservation throughout the year (Stewart, 2016). The system focuses on retaining the precipitation in the land, reducing evaporation from the soil and utilizing drought-tolerant crops that grow during periods that best fit precipitation patterns (Stewart, 2016). This system allows farmers in Garden City to grow wheat and sorghum, but not corn, which tends to be a more lucrative crop (Little, 2009). Nonetheless, for some farmers, the benefit dryland farming represents to protecting groundwater resources outweighs economic profit.

Water harvesting is another alternative source of water that can be used for irrigation. Rainwater harvesting, for example, collects rainwater when it is available and stores it for later use. This method can be used at even very small scales to water subsistence agriculture, contributing to food security. An innovative solution for water harvesting is the collection of dew and fog. A fog collector is a simple frame that supports a section of mesh; the water content in the air condenses on the surface of the collector, forming water droplets that drip into a gutter that goes to a reservoir. The system is inexpensive and fog water can be delivered to drip irrigation systems, but it requires very specific climatologic and topographic conditions, and yields are difficult to predict (Schulte and others, 2018).

Rain water harvesting in Rwanda. © Wirestock Creators / Shutterstock

Some places will have options that are unavailable to others, either due to climatological conditions or resource availability. For instance, rainwater or fog harvesting is not readily available in Saudi Arabia as the arid nation receives very little precipitation. As a solution, Saudi Arabia more strongly relies on treated wastewater for irrigation and desalinated seawater for urban needs (Chandrasekharam, 2018; Plumer, 2015) to preserve the remaining groundwater and to make sure all water needs are met. These technologies are, however, often very expensive and thus may not be an available alternative for other regions.

5.3 From Delay to Transform

Our trajectory towards groundwater depletion is driven mainly by the fact that we are extracting water from aquifers at a much faster rate than they can be recharged. Since the root causes of the problem are so diverse, it will require an equally diverse set of solutions to address the problem as a whole. Importantly, different interventions applied together as a package are more likely to delay crossing the tipping point than just a single action. Solutions to delay crossing the tipping point include technological options to improve water use in irrigation, managed aquifer recharge, along with improved rules and regulations. More can be done on this last point to transform how society values, uses and manages groundwater.

To move away from a groundwater depletion risk tipping point, we must establish a shared understanding of what constitutes the sustainable use of groundwater with an understanding that being on a finite planet means resources are already limited, and as we disrupt natural systems, we face scarcity and competition in meeting human needs. We need to establish new definitions of sustainability and resilience for our groundwater resources to balance availability and needs, considering all the users of the resource and ensuring that they are not excluded simply because of the actions of a few. Transforming our systems to ensure cooperation and trust on all scales is necessary to facilitate these solutions.

Additionally, how we value natural resources and choose to use them matters. Regulations and policies are written and implemented by people, and the values we choose to prioritize are reflected in the tools used for decision-making. As such, we need to transform our systems to take natural systems into account in planning, to see the groundwater system and human societies as part of an interconnected whole that relies on natural processes to survive. For instance, water policies should incorporate environmental considerations to ensure there is enough water for both surface and subsurface ecosystems to stay healthy. For this policy, changes are required and should include establishing optimal paths for groundwater extractions with a true consideration of ecosystems dynamics and functional health (Esteban and others, 2021).

Sustainability can be applied in a weak or strong way as it is a matter of values and choices. The continued extraction of depleted groundwater resources could be justified, for instance, by arguing it enables socioeconomic growth or that, if done for a short time period, it can provide prosperity to adapt socioeconomic structures to a sustainable future (Aeschbach-Hertig and Gleeson, 2012). Indeed, there are ways to sustainably use groundwater, but unfortunately, the observed tendency is the prioritization of profits or economic capital, rather than that of social and environmental aspects. Strong sustainable policies on groundwater extraction must be implemented to reduce its systemic use where depletion is prevalent, while management strategies should ensure current and future generations can benefit from the safety this resource can provide (Aeschbach-Hertig and Gleeson, 2012). This can only occur by adopting a vision and consideration for the future, to ensure that there is enough groundwater for future generations to use. Change comes either by disaster or by design, and we have the ability choose our present conditions that have implications for the future of our generations. We must choose a just pathway that ensures access to groundwater for all.

6. Conclusion

We are rapidly approaching groundwater depletion risk tipping points across the globe, with serious potential impacts on local livelihoods and global food security. Our actions and behaviours, such as prioritizing profits and insufficient risk management, have brought us to the brink of collapse. However, reaching a risk tipping point for groundwater depletion is not inevitable, and even some places that have crossed the threshold could be brought back. We have the benefit of seeing the risk tipping point ahead of us and can choose to take action, to sustainably balance the way we use our groundwater resources by understanding how these systems work. We can act to ensure that our societies, food security and ecosystems are resilient and sustainable, both in the present and the future.

7. References

Acreman, Michael, Robbert Casier, and Tobias Salathe (2022). Evidence-based Risk Assessment of Ecological Damage due to Groundwater Abstraction; the Case of Doñana Natural Space, Spain. Wetlands, vol. 42, No. 7, art. 63. pp. 1–16. DOI: 10.1007/s13157-022-01570-6

Aeschbach-Hertig, Werner, and Tom Gleeson (2012). Regional strategies for the accelerating global problem of groundwater depletion. Nature Geoscience, vol. 5, No. 12, pp. 853–61. DOI: 10.1038/ngeo1617

Aiken, J. David (1988). Development of the Appropriation Docterine: Adapting Water Allcoation Policies to Semiarid Environs. Great Plains Quarterly, vol. 8, No. 1, pp. 38–44. Available at https://core.ac.uk/download/pdf/17239584.pdf

Ajaz, Ali, Sumon Datta, and Scott Stoodley (2020). High Plains Aquifer–State of Affairs of Irrigated Agriculture and Role of Irrigation in the Sustainability Paradigm. Sustainability, vol. 12, No. 9, art. 3714. pp. 1–17. DOI: 10.3390/su12093714

Al Felou, Motasem (2022). Saudi Considers Wheat Growing after Price Surge. Available at https://en.majalla.com/node/217881/politicssaudi-considers-wheat-growing-after-price-surge

Ambast, Sunil K., Narenda K. Tyagi, and S. K. Raul (2006). Management of declining groundwater in the Trans Indo-Gangetic Plain (India): Some options. Agricultural Water Management, vol. 82, No. 3, pp. 279–96. DOI: 10.1016/j.agwat.2005.06.005

Ambika, Anukesh K., and Vimal Mishra (2022). Improved Water Savings and Reduction in Moist Heat Stress Caused by Efficient Irrigation. Earth's Future, vol. 10, No. 4, art. e2021EF002642. pp. 1–14. DOI: 10.1029/2021EF002642

Basso, Bruno, Anthony D. Kendall, and David W. Hyndman (2013). The future of agriculture over the Ogallala Aquifer: Solutions to grow crops more efficiently with limited water. Earth's Future, vol. 1, No. 1, pp. 39–41. DOI: 10.1002/2013EF000107

Bessire, Lucas (2021). The Next Disaster Coming to the Great Plains. Available at https://www.theatlantic.com/ideas/archive/2021/12/kansas-aquifer-ogallala-water-crisis-drought/621007/

Bierkens, Marc F. P., and Yoshihide Wada (2019). Non-renewable groundwater use and groundwater depletion: a review. Environmental Research Letters, vol. 14, No. 6, art. 063002. pp. 1–44. DOI: 10.1088/1748-9326/ab1a5f

Boulton, A. J., and P. J. Hancock (2006). Rivers as groundwater-dependent ecosystems: a review of degrees of dependency, riverine processes and management implications. Australian Journal of Botany, vol. 54, No. 2, pp. 133–44. DOI: 10.1071/BT05074

Budryk, Zack (2023). US in danger of running out of groundwater from overuse: NYT. The Hill, 29 August. Available at https://thehill.com/policy/energy-environment/4176511-four-in-10-groundwater-wells-hit-all-time-lows-in-last-decade-nyt/

Burchi, Stefano, and Marcella Nanni (2003). How groundwater ownership and rights influence groundwater intensive use management. In Intensive Use of Groundwater: Challenges and Opportunities. Llamas, M. R. and E. Custodio, eds. Lisse, The Netherlands: A.A. Balkema Publishers.

Castelvecchi, Davide (2023). Rampant groundwater pumping has changed the tilt of Earth's axis. Nature, DOI: 10.1038/d41586-023-01993-z

Chakraborty, Debaditya, and others (2023). Mitigation Measures Protect Groundwater Dependent Ecosystems: Hindsight Evidence. DOI: 10.21203/rs.3.rs-2849292/v1

Chandrasekharam, Dornadula (2018). Water for the millions: Focus Saudi Arabia. Water-Energy Nexus, vol. 1, No. 2, pp. 142–44. DOI: 10.1016/j.wen.2019.01.001

Clancy, Erin A. (1998). The Tragedy of the Global Commons. Indiana Journal of Global Legal Studies, vol. 5, No. 2, pp. 601–20. Available at https://www.repository.law.indiana.edu/ijgls/vol5/iss2/12

Conlisk, Erin, and others (2022). Evidence for the Multiple Benefits of Wetland Conservation in North America: Carbon, Biodiversity and Beyond. Point Blue Conservation Science. DOI: 10.5281/ZENODO.7388321

Convention on Biological Diversity (2018). 2.6 billion people draw their livelihoods mostly from agriculture. Available at https://www.cbd.int/article/biodiversityforfood-1

D'Odorico, Paolo, and others (2019). Global virtual water trade and the hydrological cycle: patterns, drivers, and socio-environmental impacts. Environmental Research Letters, vol. 14, No. 5, art. 053001. pp. 1–33. DOI: dalin

Dalin, Carole, and others (2017). Groundwater depletion embedded in international food trade. Nature, vol. 543, No. 7647, pp. 700–04. DOI: 10.1038/nature21403

Dalin, Carole (2020). Sustainability of groundwater used in agricultural production and trade worldwide. In Global Groundwater: Source, Scarcity, Sustainability, Security, and Solutions. Mukherjee, Abhijit, and others, eds., Elsevier. DOI: 10.1016/B978-0-12-818172-0.00025-6

Dennehy, K. F., D. W. Litke, and P. B. McMahon (2002). The High Plains Aquifer, USA: Groundwater development and sustainability. Geological Society, London, Special Publications, vol. 193, No. 1, pp. 99–119. DOI: 10.1144/GSL.SP.2002.193.01.09

Devineni, Naresh, Shama Perveen, and Upmanu Lall (2022). Solving groundwater depletion in India while achieving food security. Nature Communications, vol. 13, No. 1, art. 3374. pp. 1–9. DOI: 10.1038/s41467-022-31122-9

Devitt, Thomas J., and others (2019). Species delimitation in endangered groundwater salamanders: Implications for aquifer management and biodiversity conservation. Proceedings of the National Academy of Sciences, vol. 116, No. 7, pp. 2624–33. DOI: 10.1073/pnas.1815014116

Elhadj, Elie (2004). Camels Dont Fly, Deserts Dont Bloom: An Assessment of Saudi Arabia's Experiment in Desert Agriculture. Occasional Paper. No. 48. Available at https://www.academia.edu/20036612/Camels_Dont_Fly_Deserts_Dont_Bloom

Esteban, Encarna, Elena Calvo, and Jose Albiac (2021). Ecosystem Shifts: Implications for Groundwater Management. Environmental and Resource Economics, vol. 79, No. 3, pp. 483–510. DOI: 10.1007/s10640-021-00569-7

Fan, Ying, H. Li, and Gonzalo Miguez-Macho (2013). Global Patterns of Groundwater Table Depth. Science, vol. 339, No. 6122, pp. 940–43. DOI: 10.1126/science.1229881

Fishman, Ram, Meha Jain, and Avinash Kishore (2013). Groundwater depletion, adaptation and migration: Evidence from Gujarat, India. Available at https://www.theigc.org/publications/groundwater-depletion-adaptation-and-migration-evidence-gujarat-india-working-paper

Food and Agriculture Organization of the United Nations (1999). FAO in India: India at a glance. Available at https://www.fao.org/india/fao-in-india/india-at-a-glance/en/

Griggs, Burke W., Matthew R. Sanderson, and Jacob A. Miller-Klugesherz (2022). Farmers are depleting the Ogallala Aquifer because the government pays them to do it. Available at https://www.americanbar.org/groups/environment_energy_resources/publications/trends/2021-2022/march-april-2022/farmers-are-depleting/

Haacker, Erin M. K., Anthony D. Kendall, and David W. Hyndman (2016). Water Level Declines in the High Plains Aquifer: Predevelopment to Resource Senescence. Ground water, vol. 54, No. 2, pp. 231–42. DOI: 10.1111/gwat.12350

Halverson, Nathan (2015). What California can learn from Saudi Arabia's water mystery. Available at https://revealnews.org/article/what-california-can-learn-from-saudi-arabias-water-mystery/

Hardin, Garrett (1968). The Tragedy of the Commons. Science, vol. 162, No. 3859, pp. 1243–48. DOI: 10.1126/science.162.3859.1243

Hartmann, Andreas (2022). The Hydrology of Groundwater Systems - From Recharge to Discharge. In Encyclopedia of Inland Waters. Mehner, Thomas and Klement Tockner, eds. Oxford: Elsevier. DOI: 10.1016/B978-0-12-819166-8.00097-9

Hicks, Gloria (2007). Getting at Groundwater with Gravity. Available at https://www.earthdata.nasa.gov/learn/sensing-our-planet/getting-at-groundwater-with-gravity

Hockaday, S., and Kerri J. Ormerod (2020). Western Water Law: Understanding the Doctrine of Prior Appropriation. Available at https://extension.unr.edu/publication.aspx?PubID=3750

International Groundwater Resources Assessment Centre (2021). What is Groundwater? Available at https://www.un-igrac.org/what-groundwater

Jain, Meha, and others (2021). Groundwater depletion will reduce cropping intensity in India. Science Advances, vol. 7, No. 9, art. eabd2849. pp. 1–9. DOI: 10.1126/sciadv.abd2849

Jasechko, Scott, and Debra Perrone (2021). Global groundwater wells at risk of running dry. Science, vol. 372, No. 6540, pp. 418–21. DOI: 10.1126/science.abc2755

Jayaram, Dhanasree (2016). Why India and Pakistan Need to Review the Indus Waters Treaty. Available at https://climate-diplomacy.org/magazine/cooperation/why-india-and-pakistan-need-review-indus-waters-treaty

Kundzewicz, Zbeigniew W., and Petra Döll (2009). Will groundwater ease freshwater stress under climate change? Hydrological Sciences Journal, vol. 54, No. 4, pp. 665–75. DOI: 10.1623/hysj.54.4.665

Lankford, Bruce A. (2023). Resolving the paradoxes of irrigation efficiency: Irrigated systems accounting analyses depletion-based water conservation for reallocation. Agricultural Water Management, vol. 287, art. 108437. pp. 1–22. DOI: 10.1016/j.agwat.2023.108437

Little, Jane B. (2009). Saving the Ogallala Aquifer. Scientific American, vol. 19, No. 1, pp. 32–39. DOI: 10.1038/scientificamericanearth0309-32

Liu, Pang-Wei, and others (2022). Groundwater depletion in California's Central Valley accelerates during megadrought. Nature Communications, vol. 13, No. 1, art. 7825. pp. 1–11. DOI: 10.1038/s41467-022-35582-x

Llamas, M. R. (1989). Wetlands and Groundwater: new constraints in groundwater management-quantity and quality. Groundwater Management: Quantity and Quality. IAHS-AISH publication, vol. 188, 595-604.

Luxem, Katja (2017). Managed Aquifer Recharge. Available at https://www.americangeosciences.org/sites/default/files/CI_Factsheet_2017_6_MAR_170921.pdf

Margat, Jean, and Jac Van der Gun (2013). Groundwater around the World: A Geographic Synopsis, 1st edition, Hoboken: CRC Press

Ministry of Jal Shakti (2021). National Compilation on Dynamic Ground Water Resources of India 2020. Available at http://cgwb.gov.in/sites/default/files/MainLinks/2021-08-02-GWRA_India_2020.pdf

Mousa, Hussein (2022). Food and Agricultural Import Regulations and Standards Country Report, SA2022-0011. Riyadh, Saudi Arabia: U.S. Department of Agriculture Foreign Agricultural Service: Saudi Arabia. FAIRS Annual Country Report.

Mu, Mengyuan, and others (2022). How do groundwater dynamics influence heatwaves in southeast Australia? Weather and Climate Extremes, vol. 37, pp. 1–12. DOI: 10.1016/j.wace.2022.100479

Müller, Marc F., Michèle C. Müller-Itten, and Steven M. Gorelick (2017). How Jordan and Saudi Arabia are avoiding a tragedy of the commons over shared groundwater. Water Resources Research, vol. 53, No. 7, pp. 5451–68. DOI: 10.1002/2016WR020261

Novo, Cristina (2019). Saudi Arabia's groundwater to run dry. Available at https://smartwatermagazine.com/blogs/cristina-novo/saudi-arabias-groundwater-run-dry

Oteng-Peprah, Michael, Mike A. Acheampong, and Nanne K. deVries (2018). Greywater Characteristics, Treatment Systems, Reuse Strategies and User Perception-a Review. Water, Air, and Soil Pollution, vol. 229, No. 8, art. 255. pp. 1–16. DOI: 10.1007/s11270-018-3909-8

Panagopoulos, Argyris, and Katherine-Joanne Haralambous (2020). Environmental impacts of desalination and brine treatment - Challenges and mitigation measures. Marine Pollution Bulletin, vol. 161, Part B, art. 111773. pp. 1–12. DOI: 10.1016/j.marpolbul.2020.111773

Pandey, Vagish V., and others (2022). Challenges and issues of groundwater management in India. Current Science, vol. 123, No. 7, pp. 856–63. DOI: 10.18520/cs/v123/i7/856-864

Plumer, Brad (2015). Saudi Arabia squandered its groundwater and agriculture collapsed. California, take note. Available at https://www.vox.com/2015/9/14/9323379/saudi-arabia-squandered-its-groundwater-and-agriculture-collapsed

Qadir, Manzoor, and Christopher A. Scott (2023). Trade-offs of wastewater irrigation. In Encyclopedia of Soils in the Environment. Goss, Michael J. and Margaret A. Oliver, eds. San Diego: Elsevier Science & Technology. DOI: 10.1016/B978-0-12-822974-3.00018-5

Richey, Alexandra S., and others (2015). Quantifying renewable groundwater stress with GRACE. Water Resources Research, vol. 51, No. 7, pp. 5217–38. DOI: 10.1002/2015WR017349

Richmond, Terese, Jenna R. Mandell-Rice, and Rachael L. Lipinski (2021). The Purposeful Tension Within the Doctrine of Beneficial Use. Available at https://www.natlawreview.com/article/purposeful-tension-within-doctrine-beneficial-use

Rodella, Aude-Sophie, Esha Zaveri, and François Bertone (2023). The Hidden Wealth of Nations: The Economics of Groundwater in Times of Climate Change. Washington, DC: World Bank. Available at https://www.worldbank.org/en/topic/water/publication/the-hidden-wealth-of-nations-groundwater-in-times-of-climate-change.pdf

Sanderson, Matthew R., and Vivian Hughes (2019). Race to the Bottom (of the Well): Groundwater in an Agricultural Production Treadmill. Social Problems, vol. 66, No. 3, pp. 392–410. DOI: 10.1093/socpro/spy011

Schreiner-McGraw, Adam P., and Hoori Ajami (2021). Delayed response of groundwater to multi-year meteorological droughts in the absence of anthropogenic management. Journal of Hydrology, vol. 603, Part B, art. 126917. pp. 1–10. DOI: 10.1016/j.jhydrol.2021.126917

Schulte, Achim, René Suthfeld, and Benjamin Vogt (2018). Application, advantages and disadvantages of fog harvesting. In: E-Learning Project IWRM - Integrated Water Resources Management. Department of Earth Sciences, Freie Universität Berlin. Available at https://www.geo.fu-berlin.de/en/v/iwrm/Implementation/technical_measures/Water-harvesting-techniques/fog_harvesting/application_adv_disadvant_fog/index.html

Shiao, Tien, and others (2015). 3 Maps Explain India's Growing Water Risks. Available at https://www.wri.org/insights/3-maps-explain-indias-growing-water-risks

Siebert, S., and others (2015). A global data set of the extent of irrigated land from 1900 to 2005. Hydrology and Earth System Sciences, vol. 19, No. 3, pp. 1521–45. DOI: 10.5194/hess-19-1521-2015

Stewart, Bob A. (2016). Dryland Farming. Reference Module in Food Sciences, DOI: 10.1016/B978-0-08-100596-5.02937-1

Stumpp, Christine, and Grant C. Hose (2013). The Impact of Water Table Drawdown and Drying on Subterranean Aquatic Fauna in In-Vitro Experiments. PloS ONE, vol. 8, No. 11, art. e78502. 1-10. DOI: 10.1371/journal.pone.0078502

Taylor, Richard, and Mohammad Shamsudduha (2022). Groundwater: depleting reserves must be protected around the world. Available at https://theconversation.com/groundwater-depleting-reserves-must-be-protected-around-the-world-179620

The Times of India (2022). Punjab contributed 31% wheat, 21% rice to country's food reserves. The Times of India, 30 December. Available at https://timesofindia.indiatimes.com/city/chandigarh/state-contributed31-wheat-21-rice-to-countrys-food-reserves/articleshow/96610974.cms

UN Water (2021). Progress on Transboundary Water Cooperation – 2021 Update: Global status of SDG indicator 6.5.2 and acceleration needs. Available at https://www.unwater.org/publications/progress-transboundary-water-cooperation-2021-update

__________ (2022). The United Nations World Water Development Report 2022: Making the invisible visible. Paris: UNESCO

United Nations, and United Nations Educational, Scientific and Cultural Organization (2018). Progress on transboundary water cooperation: Global baseline for SDG indicator 6.5.2. Paris, France. Available at https://www.unwater.org/sites/default/files/app/uploads/2019/10/Indicator-652_UNECE_EN.pdf

van der Kooij, Saskia, and others (2013). The efficiency of drip irrigation unpacked. Agricultural Water Management, vol. 123, pp. 103–10. DOI: 10.1016/j.agwat.2013.03.014

Vasco, Donald W., and others (2019). Satellite-based monitoring of groundwater depletion in California's Central Valley. Scientific Reports, vol. 9, No. 1, art. 16053. pp. 1–14. DOI: 10.1038/s41598-019-52371-7

Wattoo, Khalid S., and Sara Mehmood (2022). Groundwater export, 2022. Available at https://www.dawn.com/news/1715448

Xu, Li, and James S. Famiglietti (2023). Global patterns of water- driven human migration. Wiley Interdisciplinary Reviews: Water, vol. 10, No. 4, art. e1647. DOI: 10.1002/wat2.1647

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