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Regional strategies for the accelerating global problem of groundwater depletion

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Groundwater—the world's largest freshwater resource—is critically important for irrigated agriculture and hence for global food security. Yet depletion is widespread in large groundwater systems in both semi-arid and humid regions of the world. Excessive extraction for irrigation where groundwater is slowly renewed is the main cause of the depletion, and climate change has the potential to exacerbate the problem in some regions. Globally aggregated groundwater depletion contributes to sea-level rise, and has accelerated markedly since the mid-twentieth century. But its impacts on water resources are more obvious at the regional scale, for example in agriculturally important parts of India, China and the United States. Food production in such regions can only be made sustainable in the long term if groundwater levels are stabilized. To this end, a transformation is required in how we value, manage and characterize groundwater systems. Technical approaches—such as water diversion, artificial groundwater recharge and efficient irrigation—have failed to balance regional groundwater budgets. They need to be complemented by more comprehensive strategies that are adapted to the specific social, economic, political and environmental settings of each region.

It is widely recognized that water is a critical[1] and vulnerable[2] resource, and groundwater plays a pivotal role in this complex issue[3,4]. As groundwater largely defies direct observation, its dynamic and interconnected nature is difficult to grasp even for experts[5]. Moving slowly through the pore space of permeable geological units called aquifers, groundwater is an active part of the hydrologic cycle, often closely linked to surface water features such as rivers, lakes or wetlands[5,6]. But its flux, storage and residence time markedly differ from other parts of the hydrologic cycle (Fig. 1a).

Groundwater represents by far the largest store of unfrozen freshwater on the Earth (Fig. 1a). It is more widely accessible and less vulnerable to quality degradation and droughts than surface water[3,7]. Even in regions with abundant surface water, groundwater is often an important source of drinking water. But about 90% of the global consumptive water use is for irrigation[8,9], and about 40% of the irrigation water is derived from groundwater[9,10]. In arid parts of the world, groundwater is often the only available water resource to support or expand agricultural production. As irrigated agriculture contributes about 40% of global food production[11], increased groundwater extraction (removal of groundwater from the subsurface, also called abstraction or pumping) for irrigation has contributed substantially to the 'green revolution' and to an expanded global food supply[1,3,4,12,13]. At the same time, however, it has led to groundwater depletion (a permanent decrease in storage, meaning the volume of water stored in aquifers) in many parts of the world[3,4,7,8]. Although the impact of groundwater extraction is most acute and obvious at local scales, groundwater depletion can be considered a global problem[14] owing to its widespread distribution and its potential consequences for water and food security and for sea-level rise.

The effects of groundwater depletion are complex and dependent on the aquifer, although a number of problems are common[3,14]. The most direct effect is a lowering of water tables. This leads to increased cost of pumping or drying up of wells, thus affecting users[15,16]; reduced groundwater discharge to streams, springs and wetlands, affecting ecosystems[17]; and land subsidence, irreversibly reducing storage and potentially damaging infrastructure[12]. Lowered water tables induce groundwater flow, which can lead to salinization by saltwater intrusion in coastal regions or by leakage from adjacent layers that contain saline water[3,14]. Similarly, groundwater depletion can promote the spread of other types of pollution.

Groundwater quality and contamination are important concerns in themselves[3,18,19], although largely beyond the scope of this Review. For example, groundwater can also be salinized by salt mobilization in irrigated regions, or by brines and industrial activity[3]. Contamination from nutrients and pesticides can be widespread, insidious and difficult to detect in agricultural regions[19]. In urbanized or industrial regions, groundwater can be contaminated by a broad suite of dissolved and non-aqueous chemicals[3]. There are also important groundwater quality problems of natural origin, most notably high levels of arsenic and fluoride in some regions[12,20].

Global and regional extent of groundwater depletion

Groundwater depletion is a global issue whose magnitude was poorly known until recently[14]. The existence of a groundwater quantity problem on the global scale has even been recently questioned[12], given that global groundwater extractions (~1,500 $km^3\ yr^{-1}$)[10] are small compared with global recharge (~12,600 $km^3\ yr^{-1}$; Fig. 1a)[21,22]. Yet depletion of aquifers is a reality in many regions, primarily shown by rapid declines of groundwater levels measured locally in wells[23,24] and more recently demonstrated at the basin scale by gravity measurements from the GRACE satellites[25–27]. GRACE data are suitable to monitor large-scale changes in groundwater storage, but high-resolution monitoring data for groundwater levels remain indispensable because depletion can be highly localized[24].

Several recent studies have estimated the magnitude of groundwater depletion on a global scale, in order to examine the contribution of decreased continental water storage to sea-level rise[10,23,28–30]. The results differ substantially (Fig. 1b), owing to different estimation methods. The lowest estimates of the cumulative global

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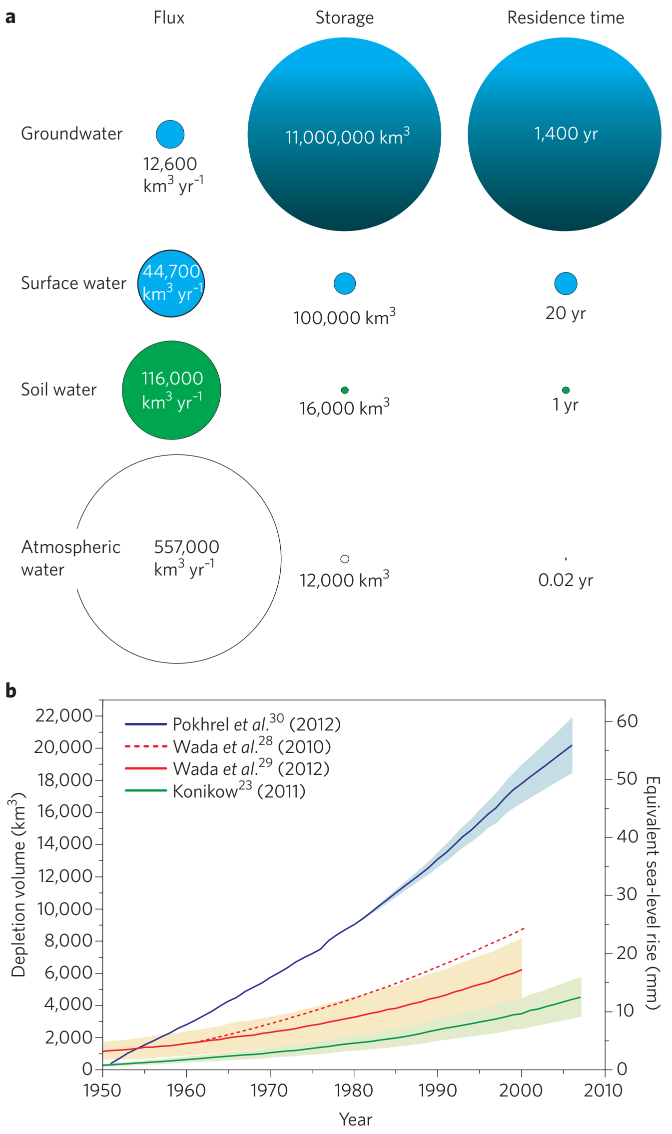

Figure 1 | Characteristics of the global water cycle and the rate of groundwater depletion and corresponding sea-level rise for the period 1950–2010. a, The global average annual input flux, total storage and residence time of groundwater, surface water, soil water and atmospheric water. The areas of the circles are scaled based on assessments of world water resources[82,83] and groundwater recharge[21]. Circles are coloured based on the classification of green water (soil water available to plants), blue water (surface water and groundwater) and dark blue water (non-renewable groundwater)[84–86]. **b**, Estimates of cumulative global groundwater depletion[23,28,30] with shaded areas illustrating reported uncertainties of the individual estimates. The dashed red line was obtained by integration of annual depletion rates from 1960 to 2000 (ref. 29) and adopting the estimate for pre-1960 cumulative depletion from a later study that contains corrections for capture effects (full red line[30]).

groundwater depletion were obtained by the most direct approach using water-level and GRACE data in conjunction with groundwater flow models[23]. Because comprehensive data are available for few aquifer systems, estimating global groundwater depletion with this approach requires extrapolation[23,29,31] and the result may be too low[31]. Higher estimates of groundwater depletion (Fig. 1b) were calculated as the difference between natural groundwater recharge from a global hydrologic model and groundwater extraction from national statistics[28]. This method may overestimate groundwater depletion[23,31], as it does not account for recharge from irrigation and surface water bodies as well as the dynamic response of groundwater systems to extraction (that is, capture; see Box 1). Correcting for this bias leads to somewhat lower depletion estimates[29]. The highest estimate of groundwater depletion (Fig. 1b) was derived from a global hydrologic model that assumes groundwater can be withdrawn from an infinite reservoir based on demand[30]. This method probably significantly overestimates depletion because aquifers are not infinite reservoirs. Figure 1b indicates that the uncertainty about the magnitude of global groundwater depletion is considerable. The different studies agree, however, that depletion rates have accelerated markedly since the mid-twentieth century and by now represent a non-trivial contribution to the rate of sea-level rise. The rate of groundwater depletion is projected to accelerate further in the future[29].

Although the global sum of groundwater depletion is important, depletion is limited to certain regions, where local and regional aquifer systems are overexploited[32]. Figure 2a shows the magnitude and geographical distribution of regional groundwater depletion. The most affected regions include parts of India, northeastern China, the western United States, Mexico, Iran, Saudi Arabia and parts of northern Africa. In the following we briefly report on the current state of depletion and the hydrologic settings of aquifers in Northern India, northeastern China and the western United States, to which we will later return as examples for various groundwater management and policy measures.

The largest rates of depletion currently occur in the Indo-Gangetic Plain, encompassing northern India and Bangladesh as well as parts of Pakistan and Nepal (Fig. 2a). Recent GRACE data have highlighted the extent of groundwater depletion in northwestern India[25] as well as the entire Indo-Gangetic basin[33]. The fertile sedimentary plains of the Indus and Ganges river systems cover about 700,000 km^2 and are home to about 1 billion people. Agriculture in the region is intense, and irrigation by surface water has been practised for millennia[34]. Beginning around 1970, however, the availability of well-drilling equipment and electrical pumps has revolutionized irrigated agriculture. Irrigation in the region has transformed from centrally managed surface-water distribution to a regime where tens of millions of wells operate largely unregulated. India now pumps more than twice as much groundwater as the United States or China[16,34].

The large aquifer system of the North China Plain plays a central role in China's food production, as the region supplies more than half of China's wheat and one-third of its maize[35]. The North China Plain covers 320,000 km^2 and is home to more than 200 million people[36]. Agricultural production in the region has grown markedly in the past decades, strongly benefiting from the fast-growing groundwater exploitation[37], but the sustainability of this production seems threatened by widespread declines in groundwater level, locally at a rate of more than 1 m per year[36,38]. The strong increase of evapotranspiration due to the intensive cropping system has led to an imbalance in the groundwater budget, which has been confirmed by recharge estimates based on groundwater ages[39] (Box 1).

Two prominent examples of overexploited aquifer systems are the High Plains and California Central Valley aquifers in the United States[24]. These systems are comparatively well studied, with depletion estimates based on water levels of thousands of wells[24] as well as on GRACE satellite data[26,27]. In both systems, the depletion is localized. For example, about a third of the depletion in the High Plains aquifer system occurs in just 4% of its area[24]. In the northern part of the High Plains, natural recharge is comparatively high and declines of storage are small. In contrast, in the central and southern High Plains, recharge rates are low and irrigation depletes the storage of groundwater, some of which was recharged up to 13,000 yr ago as indicated by ^{14}C dating[40] (Box 1). In the Central Valley, precipitation is very low, and water is imported by rivers and large-scale diversion

Box 1 | Groundwater budgets and ages

The groundwater budget[35,41,43–44,46] consists of several components (Fig. B1). The change of storage in the part of the groundwater system considered equals the sum of inflows (recharge, *R*, lateral groundwater inflow, GW) minus the sum of outflows (discharge, *D*, evapotranspiration, ET, and extraction, *E*). Before development, steady-state conditions (that is, constant storage) can be assumed[90] because hydrologic fluctuations are modulated by the long residence time of water in aquifers (Fig. 1a). Extraction of groundwater from a well initially reduces storage and causes a depression of the hydraulic head—the combination of pressure and elevation that drives groundwater flow—that spreads outward from the well[90]. The ensuing re-arrangement of the water table can lead to increased recharge as well as decreased discharge and evapotranspiration, the overall effect of which is called capture[46]. It can also lead to increased lateral flow from adjacent aquifers or watersheds. If the extracted water is used for irrigation, evapotranspiration increases and a possible return flow of excess irrigation water adds to the total recharge. It is important to note that none of the estimates of global groundwater depletion have consistently accounted for all of the terms in the groundwater budget, especially lateral groundwater flow.

Eventually, a new equilibrium state is reached, in which the extraction is balanced by capture and thus storage is no longer depleted. Although physically sustainable, the changes in the hydrologic system in this new state may have significant and undesirable environmental, social or economic impacts[24,38,44]. The time needed for the hydraulic configuration of the system to equilibrate after the perturbation exerted by the extraction is given by the hydraulic response time[5,44,46]. It varies over many orders of magnitude, from hours to hundreds of thousands of years[5], depending on the size of the aquifer system and its hydraulic properties. If the stress applied to a groundwater system is too large, that is if capture cannot ultimately compensate for extraction, a new equilibrium is impossible and the system has a finite life[44,46].

Although the hydraulic response time helps to quantify the response of aquifers to extraction, the residence time or groundwater age is more useful for quantifying recharge rates and the transport of contaminants to wells[91]. The residence time of an aquifer is defined as the average time for groundwater to flow from recharge to discharge areas, whereas groundwater age is the travel time that has passed since the water infiltrated into the subsurface[5,92]. The residence time can be used to estimate the renewal rate of groundwater reserves and could be used for the time horizon for setting long-term sustainability goals for aquifers[61]. Groundwater age is a frequently used indicator in hydrogeology, as it can quite directly be measured by a variety of tracer methods[93,94]. Groundwater ages from days up to a million years[95] have been found by such methods. Old groundwater, as often found in deeper parts of large aquifers[40,95,96], indicates that such reserves have to be regarded as non-renewable under current conditions (dark blue water, Box 2). Younger ages, often in the range of years to decades, are found in shallow aquifers and are important in assessing the vulnerability of wells to contamination. On the one hand, the slow flow of groundwater protects wells from contamination sources at the surface; on the other hand, it delays the effect of measures taken to improve groundwater quality[19,97].

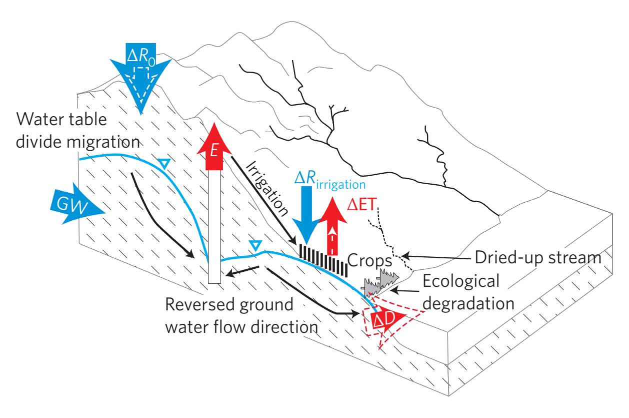

Figure B1 | The fluxes in and out of groundwater systems. The inputs are shown in blue and the outputs are shown in red with the size of the arrows representing typical fluxes. The water table is the solid blue line (marked by blue inverted triangles) in this unconfined aquifer where the groundwater is directly connected to surface water bodies and ecosystems. In natural, steady-state conditions before groundwater development, natural recharge (R_0) is balanced by evapotranspiration (ET_0) of groundwater-dependent plants and groundwater discharge (D_0) with arrows shown in dashed lines. Development through extraction (*E*) can increase recharge (ΔR_0) and induce regional groundwater flow (GW), as well as decrease groundwater discharge (ΔD_0). Using the pumped water for irrigation increases evapotranspiration (ΔET) and recharge owing to irrigation return flow ($\Delta R_{\text{irrigation}}$). Changes in groundwater storage are shown by the lowering of the water table.

of surface water. These diversion projects have led to a partial recovery of aquifer storage, but depletion still continues, especially during episodic droughts[24].

Explanations for groundwater depletion are complex and dependent on the aquifer examined as well as on the perspective, training and background of the examiner. For example, groundwater depletion can be explained by a hydrologist as the result of an imbalance between the inputs and outputs of the system, whereas a social scientist in economics, policy studies or sustainability science may consider its root cause to be policy, regulation or management of water, land or agriculture. We first summarize the hydrologic perspective on groundwater depletion and management and then examine the issue using a broader socioeconomic and policy perspective.

Balancing groundwater budgets

Groundwater depletion occurs when the water output from an aquifer exceeds the input. Although this simple statement is correct, it is important to examine groundwater budgets in more detail[5,41], recognizing that groundwater extraction dynamically alters aquifer inputs and outputs (Box 1). Early groundwater regulation often erroneously suggested that the safe yield of a groundwater basin is the rate of natural groundwater recharge[42]. This 'water budget myth'[41,43,44] ignores the fact that groundwater extraction leads to increased recharge and/or decreased discharge, also called capture (Box 1). For example, extraction from major aquifer systems in the United States has led to changes in all components of the water budget: recharge, discharge and storage[5]. Application of the safe yield concept in areas such as the High Plains aquifer has led to dried-up streams and ecological degradation[17,45].

Groundwater systems thus have to be understood as complex systems that react dynamically to the perturbation introduced by extraction. Because of the long hydraulic response times of aquifers (see Box 1), a new equilibrium state with constant storage may not easily be reached on human timescales[46]. Additional complications

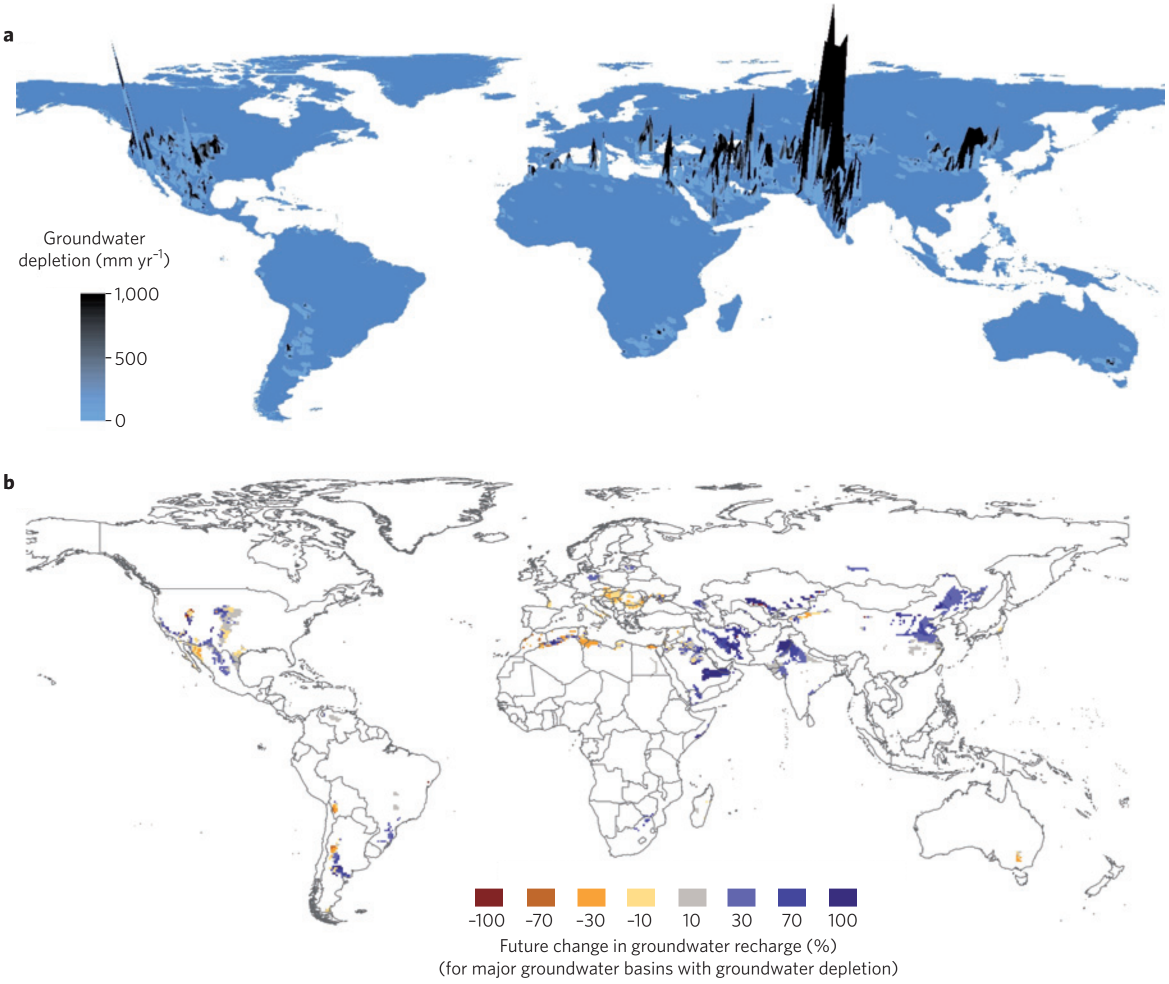

Figure 2 | Global groundwater depletion and the potential for changes in groundwater recharge in areas of groundwater depletion. a, A recent estimate of the global distribution of groundwater depletion[29] is remapped as three-dimensional topography to show 'mountains of groundwater depletion' especially 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; see Box 2). **b**, The potential change in groundwater recharge for 2041–2070 relative to 1961–1990 has been simulated for four climate change scenarios[21]. Here we show the potential change in recharge for IPCC greenhouse gas emissions scenario A2, translated into climate change scenarios in the ECHAM4/OPYC3 global climate model, for major groundwater basins[80] with groundwater depletion from **a**.

arise from variations in the boundary conditions due to changes in climate and land use. Assessments of the water balance of aquifers therefore need to account for the dynamic development of the system and cannot only examine natural recharge and planned rates of extraction[44]. Nevertheless, it makes sense to discuss groundwater depletion and management options in terms of recharge and extraction, which are the most important and easily managed components of groundwater budgets. Water management strategies can be classified as demand-side strategies that aim at decreasing groundwater extraction and supply-side strategies that try to increase the water supply in general and specifically the groundwater recharge[12,16,47]. We first examine extraction and related demand-side strategies and then discuss factors influencing recharge along with possible supply-side strategies.

Groundwater extraction directly affects the water budgets of aquifers, and Fig. 3a indicates that it may be a main factor in groundwater depletion[4,31]. In many important groundwater basins, depletion amounts to a sizeable fraction of total groundwater extraction (7–87% for national averages[4,31]). Groundwater extraction strongly depends on irrigation patterns, methods and efficiencies because most of the global consumptive water use is for the purpose of irrigation[8,9]. Increasing demand for groundwater is thus ultimately driven by increasing demand for food, which in turn is due to population growth and shifting diets[48]. For example, population pressure seems to be an important driver of well density in South Asia[16].

Given that groundwater depletion is linked with irrigated agriculture, it is important to examine irrigation practices. Improved irrigation efficiency is often suggested[12,35] as a way to reduce water demand and thus extraction. But for agricultural areas with shallow aquifers, groundwater depletion is largely controlled by the rate of evapotranspiration rather than the rate of extraction *per se*, because excess extracted groundwater returns to the aquifer[35]. For this reason, the reduction of extraction for irrigation that occurred in the North China Plain after the mid-1970s did not reduce the decline rate of groundwater tables[36]. In the High Plains, water-saving irrigation has allowed farmers to irrigate more land. This leads to higher evapotranspiration at the expense of irrigation return flow, thereby counter-intuitively increasing aquifer depletion[35].Increased irrigation efficiencies can also lead to soil salinization[12,24]. Ultimately, groundwater depletion is inevitable if irrigation based on groundwater raises crop evapotranspiration to levels above water inputs to the region through precipitation and inflow[35]. Instead, rates of groundwater depletion can be decreased by growing less crop or irrigating less area, although this is typically not as politically attractive as using technology to increase irrigation efficiency[35]. From a water management perspective, compensating for a shortage of water by importing food representing 'virtual water' (Box 2) could be an attractive option for some countries[49,50]. One option to reduce groundwater depletion while maintaining agricultural production could be to optimize conjunctive use of ground and surface water for irrigation[14,16], although groundwater irrigation is generally more productive[12,16], and conjunctive use is of limited value in regions with little surface water, such as the southern High Plains[24].

Groundwater depletion also depends on the availability of water to replenish groundwater reserves, suggesting that arid regions are more vulnerable to the effects of extraction. Yet Fig. 3b shows that groundwater depletion is most common in semi-arid and humid regions, suggesting that extraction currently tends to dominate over climatic factors governing recharge. Climate-related changes to aquifers have so far been small compared with non-climate drivers[51,52]. Although groundwater systems have been shown to respond to historic climate change[53,54], to our best knowledge no case of major regional aquifer depletion has been explained by historic climate change. In the future, however, climate-related changes in recharge rates[52] could affect rates of groundwater depletion.

Predicting climate-change effects on groundwater is challenging[47,52], and uncertainties are present in all steps of the process, from greenhouse gas emission scenarios to global climate models and the downscaling methods applied to adapt their projections to the scale of aquifers, and finally to hydrologic models and the effects of climate change on vegetation and recharge dynamics[21,47,55–57]. The largest single source of uncertainty may be the choice of a global circulation model[51,57], as these models differ substantially in their predictions of relevant climate variables such as precipitation[21,55]. A global assessment of the vulnerability of groundwater resources to climate change impacts found the highest vulnerabilities in northern and southwestern Africa, northeastern Brazil and the central Andes[21]. Some of these regions are already affected by groundwater depletion (Fig. 2a), and reduced recharge rates may be an additional stress factor (Fig. 2b). Recharge is predicted to increase in other regions of groundwater depletion. We stress that Fig. 2b is a preliminary spatial comparison of groundwater depletion with recharge predictions from a single emission scenario, single global climate model and single hydrologic model.

Supply-side management options aim to increase groundwater recharge by technical measures. For example, groundwater is artificially recharged in some areas such as the Central Valley[24], in some cases using treated wastewater. Artificial recharge schemes have also been proposed for the North China Plain[37] and India[34]. Compared with water storage in surface reservoirs, subsurface storage generally does not suffer from evaporation losses. For India, a promising strategy may be to convert existing canal networks into large-scale artificial recharge systems[34]. A 'hard path'[58] measure to increase water supply is large-scale water diversions, as historically realized in the Central Valley[24]. An even bigger scheme, the south–north water transfer project[59], will supply water from the wet south of China to its dry north. But even such a gigantic project might not suffice to close the gap between precipitation and evapotranspiration in the North China Plain[38], and the social, economic and ecological costs of such projects are high[58].

Groundwater sustainability and governance

Recognizing the flaws of the water budget myth and the safe yield concept as well as the limitations of purely technical management strategies, a broader and more interdisciplinary practice of groundwater management is evolving[17,42,44]. The broader concept of groundwater sustainability generally suggests[17,42–44,60–62] (1) integrating the management of groundwater and surface water, including effects on groundwater-dependent ecosystems; (2) acknowledging that decisions about groundwater use are always value-driven; (3) incorporating a long-term or multigenerational perspective; (4) managing adaptively and inclusively by stakeholders; (5) balancing the environment, society and economy; and (6) recognizing that groundwater use always affects the environment because groundwater is derived from storage and/or capture. This concept of groundwater sustainability is consistent with the general concept of sustainability[63,64] as well as integrated water-resource management, water security[65] and the 'soft path' of water management[58,66].

Groundwater management in Texas exemplifies many of these sustainability principles. The Texas Water Development Board is using groundwater models, setting long-term goals and backcasting: that is, working backward from long-term goals to identify policies and programs that will connect future goals to the present (Fig. 4)[61,67]. Groundwater management areas in the High Plains and other regions of Texas are required to set goals on 50-year time

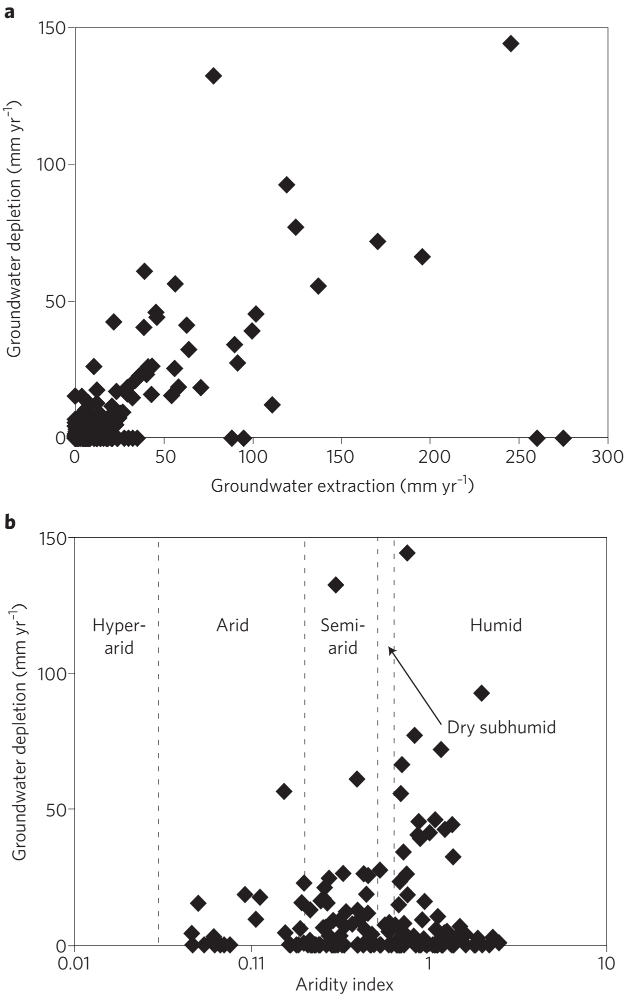

Figure 3 | Groundwater depletion for major groundwater basins in relation to extraction and aridity. a, Areal-averaged groundwater depletion[29] versus areal-averaged groundwater extraction[31] for major groundwater basins[87]. High rates of extraction correlate to high rates of depletion for major groundwater basins with groundwater depletion, partly because depletion is derived in part from extraction[31]. **b**, Areal-averaged groundwater depletion[29] plotted against areal-averaged aridity index[88] classified following UNEP[89]. The aridity index is the mean annual precipitation divided by the mean annual potential evapotranspiration. Major groundwater basins with groundwater depletion problems are most common in semi-arid to humid regions and less common in arid regions.

Box 2 | Fresh perspectives on fresh water

The widespread depletion of groundwater suggests that fresh perspectives on how we value, manage and characterize groundwater, including recent ideas such as strong sustainability, virtual and green water, could be useful in the future[60]. An important debate is whether to apply 'weak' or 'strong' sustainability to groundwater. Previous discussions of groundwater sustainability have generally considered weak sustainability, where all forms of capital (natural, human, economic and so on) are considered interchangeable. Applying weak sustainability principles to groundwater use implies that depletion of natural groundwater capital can be balanced by growth of another type of capital. For example, groundwater mining (consistent groundwater depletion) has been discussed[98] or advocated[99] to enable socio-economic growth in arid areas such as the Middle East. In contrast, strong sustainability principles[100] suggest that groundwater could have a non-interchangeable capital value[101]. Important considerations in the debate of strong versus weak sustainability are whether groundwater can be substituted by any other resource[102] and also essential socially, economically or environmentally. In some cases, groundwater may be substituted by surface water, desalinated sea water or treated waste water[98]. In some areas, a short period of unsustainable use of groundwater may provide prosperity to adapt socioeconomic structures to future sustainable use. But groundwater mining is unsustainable and potentially short-sighted because the social, economic and environmental impacts of significant groundwater depletion may be nonlinear and difficult to predict or manage. Groundwater depletion in India, for example, has not uniformly affected all economic classes but disproportionately affected the poor, who are more vulnerable[16]. Additionally, groundwater mining reduces the ability of an aquifer to provide social, environmental and economic resilience because long-term storage is being depleted[98]. Implementing strong sustainability implies that groundwater extraction should be reduced locally where systemic depletion is prevalent. Groundwater usage and protection strategies could be accomplished by setting long-term goals in an adaptive management framework (Fig. 4), and could be beneficial for both current and future generations.

The 'virtual water' and 'green water' concepts also provide a fresh perspective for discussing groundwater depletion. Virtual water is the volume of fresh water used to produce a commodity, good or service along the various steps of production[49,103,104]. The components of virtual water are green water (soil water available to plants), blue water (surface water and groundwater) and grey water (polluted water)[84,85]. In this context, non-renewable groundwater could be 'dark blue water' (rather than 'black water'[86] which can be confused with waste water), and we consider this term useful (Figs 1 and 2) to differentiate groundwater with different residence times (Box 1). Importing virtual water embedded in food has been suggested as a possible solution to water scarcity problems in the Middle East[49].

The sum of virtual water used by a group or nation is the water footprint. The global trade of virtual water and the water footprint of nations and humanity have been quantified[50,77,104]. Rich, water-poor nations tend to be virtual water importers[50]. Recently, a methodology for calculating the groundwater footprint has been developed and applied globally to regional-scale aquifers[32]. Because groundwater depletion is often driven by irrigation for agriculture, fresh approaches to water consumption in agriculture may also be useful. By dividing the components of virtual water into green, blue, grey and dark blue water, productivity (crop per drop) can be examined. Green water management in agriculture could lead to decreased groundwater depletion by changes such as rainwater harvesting, supplementary irrigation, and soil and nutrient management[84].

horizons based on priorities derived from stakeholder consultation. Goals vary from protecting flows of ecologically significant springs to maintaining water levels at specified elevations. Groundwater models are developed to predict the maximum sustainable extraction rate based on the long-term goals. Extraction rates are then set on 5-year time horizons so that each groundwater management area can re-examine short-term policies and programmes every 5 years as part of an adaptive management strategy (Fig. 4).

The broader perspective on groundwater management and sustainability shifts the focus from hydrology and technical measures towards policy and governance. This perspective adds the complexity of different political and socioeconomic systems to the various hydrologic conditions of aquifer systems, suggesting that no single method of governance can be universally applied[68]. The diverse forms of groundwater governance have been categorized as regulatory, economic and voluntary[68], and we will discuss these briefly. Box 2 describes some potential future advances in groundwater management, policy and sustainability.

Improved legal and policy frameworks to regulate groundwater use are often called for[69–71]. An international survey showed that groundwater is typically owned by governments that permit or license usage and managed by national and/or regional governments with policies of conservation, sustainable management or equal access to water for all[70]. Legislation on the use and protection of groundwater is generally more advanced in developed countries[12,70], but basic legal doctrines on groundwater rights can also differ within countries, such as the different states that share the High Plains aquifer in the United States[71]. Implementation is as important as regulation but difficult in many developing countries, where enforcement is complicated by the large number of well owners[16,72].

From an economic perspective, groundwater can be classified as a common-pool resource[61,68,71,73] subject to the 'tragedy of the commons' wherein users have no incentive to limit extraction to a socially desirable level, resulting in depletion. But resources are in fact more often depleted by the 'tragedy of open access', and inclusive and effective local governance of common-pool resources is possible without privatizing or commodifying the resource[73]. Alternatively, a typical economic strategy to manage groundwater extraction[74] is water pricing, but so far this approach has mostly been applied in urban and industrial sectors rather than in agriculture, possibly because it is difficult to implement in settings with numerous self-supplying users[12].

Another important economic governance measure is energy pricing, as energy policy and management is an important control of groundwater usage in some regions, a relation that has been termed the (ground)water–energy nexus[72,75]. The attractiveness of groundwater for individual users can depend more directly on the availability of cheap technology and energy than on the presence of productive aquifers with high recharge. The spatial pattern of the boom of groundwater irrigation in South Asia does not conform to the distribution of the most suitable hydrologic conditions[16]. Water scarcity and abundant electricity in the western Indo-Gangetic basin contrast with water abundance but scarce electricity in the eastern basin[72]. Self-regulation may be expected to emerge from rapidly dropping water levels, which increase the energy demand for pumping. But although the power used by irrigation pumps may account for as much as 15% of India's power consumption[34], its provision

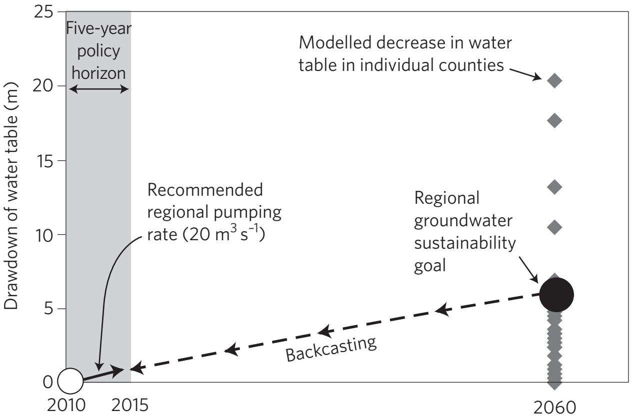

Figure 4 | Setting long-term goals and backcasting as groundwater management strategies by the Texas Water Development Board. Groundwater models are used to predict drawdown in individual counties for 2060. Stakeholders then decide on a regional groundwater sustainability goal (5.2 m of water-table drawdown) which leads to a recommended regional extraction rate over a 5-year policy horizon[61,67].

to farmers is highly subsidized or even free[15,72]. Some Indian states have introduced power metering or even power rationing for agricultural supply[16], with some success in reducing extraction for irrigation[12]. An increase in agricultural power tariffs (currently highly subsidized) has been suggested as a groundwater policy tool for Mexico, where groundwater pumping accounts for about 5% of the total electricity consumption[75].

In view of the difficulties of enforcing regulatory measures and implementing economic instruments, what is needed is voluntary compliance with management goals based on a common understanding about the common-pool resource at stake[68]. Voluntary policies are often associated with local self-governance, which seems well suited to the regional and common-pool nature of groundwater. Stakeholder participation, as in the Texas example discussed above, is an important part of voluntary governance strategies. As another example, in Andhra Pradesh, India, farmers are effectively managing groundwater resources and leading the process of data collection and analysis as part of a voluntary and collaborative project[76]. Community members use the tools, templates and techniques for estimating water availability, and groundwater depletion rates have consistently decreased.

Towards long-term regional strategies

The evidence that groundwater is being depleted is clear and unequivocal. This depletion is driven by groundwater extraction, mainly for agricultural use, in aquifers around the world. Nevertheless, the global spatiotemporal distribution of groundwater depletion needs to be quantified better. Improved measurements of groundwater usage and levels for many parts of the world are required, as well as consistent and comprehensive accounting for all groundwater inputs and outputs in observational[23] and modelling[28,29] approaches. Groundwater depletion is widespread, and its implications for sea-level rise as well as for water and food security, sustainability and vulnerability suggest that it should be considered a global problem. International trade of virtual water in the form of agricultural products (Box 2) provides a global response to regional groundwater depletion[14] and can save water globally[77]. Otherwise, however, strategies to combat groundwater depletion are only possible at a regional scale, in line with the scales of aquifers.

A long-term perspective—beyond the 5- to 20-year time horizons[61] over which groundwater is often managed—is critical, because the residence time (Fig. 1a) and the hydraulic response time (Box 1) of aquifers are much longer. This requires new tools for envisaging the future (see above and Box 2), new political priorities and better quantitative predictions of groundwater resources in a world where politics, hydrology and economics are all in flux. Groundwater modelling, necessary to devise long-term management strategies[38,78], needs to include climate scenarios[79,80] and stochastic representations of hydrologic uncertainties[78], as well as land-use[81] and water management scenarios[57]. The relative importance of changes in groundwater and land use compared with future climate change impacts for different aquifers around the world will need to be investigated.

The sustainable use of groundwater resources is an important interdisciplinary challenge—not only a question of hydrology. Any groundwater usage alters the groundwater system, and ecologic, economic, social and political factors determine the acceptable and sustainable rate of extraction[42]. The array of measures for regionally reducing net usage includes groundwater regulation, water-saving irrigation, shifts to rain-fed agriculture, imports of virtual water in the form of goods produced elsewhere, artificial recharge, rainwater preservation and indirect approaches such as energy pricing and regulation. It is critical to choose regionally adapted strategies from this range of options and generally strengthen regulation, policy and management for water, energy and agriculture[12,68,71]. There is no single solution for groundwater management, as climatic, hydrologic, political, social and economic conditions vary strongly between different affected regions. Future research needs to identify appropriate, adaptable and sustainable long-term strategies for each region and to find ways to transfer knowledge and measures between regions. Only then can change be catalysed to solve the accelerating global problem of regional groundwater depletion.

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Author contributions

Both authors contributed equally to this paper.

Additional information

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