REVIEW SUMMARY

GROUNDWATER

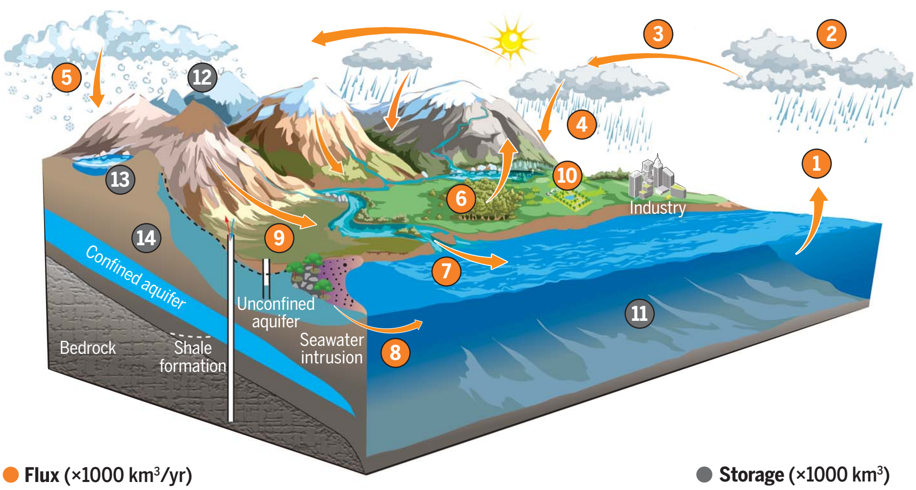
The changing nature of groundwater in the global water cycle

Xingxing Kuang, Junguo Liu*, Bridget R. Scanlon, Jiu Jimmy Jiao, Scott Jasechko, Michele Lancia, Boris K. Biskaborn, Yoshihide Wada, Hailong Li, Zhenzhong Zeng, Zhilin Guo, Yingying Yao, Tom Gleeson, Jean-Philippe Nicot, Xin Luo, Yiguang Zou, Chunmiao Zheng*

BACKGROUND: Groundwater is the largest available freshwater resource and forms an active component of the global water cycle. It serves as the primary source of fresh water for billions of people and provides drinking water to numerous communities. Moreover, groundwater supplies over 40% of global irrigation demand and is becoming increasingly important in mitigating water scarcity induced by climate change. In the past few decades, climate change and other anthropogenic activities have substantially altered groundwater recharge, discharge, flow, storage, and distribution. Climate warming–induced glacier retreat and permafrost thaw have led to changes in groundwater in glacierized and permafrost areas. In the interest of fostering a more comprehensive understanding of the state of global groundwater, we present a synthesis of its changing nature in the global water cycle over the recent decades, shaped by the impacts of climate change and other various anthropogenic activities.

ADVANCES: Climate change and other anthropogenic activities have led to regional and global transformations in groundwater dynamics. Climate-driven modifications include shifts in groundwater recharge rate across continents, increased groundwater contributions to streamflow in glacierized catchments, and profound alterations in groundwater flow patterns within permafrost areas. Glacial meltwater infiltrates into the subsurface, sustaining a stable groundwater discharge to streams during dry seasons. Permafrost thaw fosters increased rainfall infiltration, amplifies groundwater storage, creates new subsurface flow pathways, and increases groundwater discharge to streamflow. Direct anthropogenic activities include groundwater withdrawal, unconventional oil and gas production, geothermal energy exploration, managed aquifer recharge, afforestation, land reclamation, urbanization, and international food trade. These undertakings engender groundwater withdrawal and injection, reshaping regional groundwater flow regimes, impacting water tables and groundwater storage, and redistributing embedded groundwater in foods globally. Groundwater depletion occurs across the globe and has intensified over recent decades. Groundwater pumped from aquifers participates in the global water cycle by contributing to river discharge and evapotranspiration. Groundwater withdrawal transfers fresh water from long-term storage to the active water cycle at the Earth's surface. Moreover, nonrenewable groundwater withdrawal from deep aquifers integrates deep ancient fossil groundwater into the active contemporary water cycle, ultimately contributing to rising sea levels. The risks of saltwater intrusion and groundwater inundation in coastal regions are exacerbated by sea level rise. The importance of groundwater for drinking and irrigation is poised to increase in response to climate change. Consequently, the effects of groundwater depletion on sea level rise are expected to become magnified in the future.

OUTLOOK: The role of groundwater in the global water cycle is becoming increasingly dynamic and complex while the security of groundwater resources faces considerable threats worldwide in terms of both quantity and quality. The sustainable use of groundwater resources has become a crucial global concern. In planning for a more sustainable future, groundwater resources should be considered from both regional and global perspectives, especially for large, transboundary groundwater systems. As global changes continue to affect these resources, it is imperative to manage groundwater and surface water as a single resource. Additionally, ensuring food and water security and maintaining ecosystem health must be addressed concurrently. Various management strategies, including forest and wetland conservation, desalination, wastewater recycling, managed aquifer recharge, water diversion projects, and green infrastructure development may be employed to bolster the resilience of groundwater. Major research gaps exist that warrant further exploration, including detailed studies of groundwater in high-latitude and mountainous regions, more accurate predictions of groundwater recharge, quantitative assessments of injected and discharged groundwater volumes, and accurate modeling of the global water balance. To address these gaps effectively, comprehensive observational datasets are essential, as they enable a thorough evaluation of the current state and future changes in groundwater resources. ■



Flux (×1000 km^3/yr)
1 Ocean evaporation (420 ± 20%)
2 Precipitation on ocean (380 ± 20%)
3 Net water vapor flux transport (46 ± 20%)
4 Rainfall (98.5 ± 10%)
5 Snowfall (12.5)
6 Terrestrial evapotranspiration (69 ± 10%)
7 Runoff (46 ± 10%)
8 Groundwater discharge (4.5 ± 70%)
9 Groundwater withdrawal (~1.0)
10 Managed aquifer recharge (MAR) 0.01

Storage (×1000 km^3)
11 Ocean 1,338,000
12 Glaciers and snow 24,064
13 Permafrost 300
14 Groundwater 23,400

Simplified global water cycle with its components. Groundwater is becoming increasingly more dynamic in the global water cycle.

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REVIEW

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The changing nature of groundwater in the global water cycle

Xingxing Kuang[1], Junguo Liu[1,2]*, Bridget R. Scanlon[3], Jiu Jimmy Jiao[4], Scott Jasechko[5], Michele Lancia[1], Boris K. Biskaborn[6], Yoshihide Wada[7], Hailong Li[1], Zhenzhong Zeng[1], Zhilin Guo[1], Yingying Yao[8], Tom Gleeson[9], Jean-Philippe Nicot[3], Xin Luo[4], Yiguang Zou[1], Chunmiao Zheng[10,1]*

In recent decades, climate change and other anthropogenic activities have substantially affected groundwater systems worldwide. These impacts include changes in groundwater recharge, discharge, flow, storage, and distribution. Climate-induced shifts are evident in altered recharge rates, greater groundwater contribution to streamflow in glacierized catchments, and enhanced groundwater flow in permafrost areas. Direct anthropogenic changes include groundwater withdrawal and injection, regional flow regime modification, water table and storage alterations, and redistribution of embedded groundwater in foods globally. Notably, groundwater extraction contributes to sea level rise, increasing the risk of groundwater inundation in coastal areas. The role of groundwater in the global water cycle is becoming more dynamic and complex. Quantifying these changes is essential to ensure sustainable supply of fresh groundwater resources for people and ecosystems.

Groundwater is the largest available freshwater resource and constitutes a major component of the global hydrological cycle (*1*). Groundwater also provides drinking water for billions of people (*2*) and supplies ~40% of global irrigation demand (*3*), in which it is becoming increasingly important (*4–6*). As a key component of the global water cycle (Fig. 1), groundwater sustains river discharge, lakes, wetlands, crops, forests, and ecosystems (*7*). The global water cycle is being modified by climate change and other anthropogenic activities at an unprecedented rate (*8*), the effects of which need to be better understood to meet the challenges that these changes present.

Climate change is expected to fundamentally alter the global water cycle (*9*, *10*). Groundwater could mitigate the impacts of climate extremes on water resources (*11*, *12*) and is already widely used as a buffer against water scarcity during droughts (*7*). The importance of groundwater as a drinking and irrigation source is expected to increase as a result of climate change (*13*). Global warming may cause shifts in groundwater recharge rates (*7*, *14*); warming also causes accelerated glacier retreat (*15*, *16*) and permafrost degradation in high-latitude and high-altitude areas (*17*). Glacier retreat and permafrost degradation in turn lead to changes in groundwater in glacierized and permafrost areas (*18*, *19*). Lowland populations are often dependent on water resources derived from mountain headwaters as irrigation sources (*20*).

Many different anthropogenic activities have changed groundwater flow, storage, and distribution during past decades. Groundwater overexploitation occurs in many regions globally and groundwater depletion has grown in past decades (*21*). Other anthropogenic activities that can lead to changes in groundwater flow and storage include unconventional oil and gas production (*22*), geothermal energy exploration (*23*), managed aquifer recharge (*24*), afforestation (*25*), land reclamation and urbanization (*26*), and international food trade (*27*). Much of the withdrawn groundwater eventually enters the oceans and contributes to sea level rise (*28*). Rising sea levels increase the water table in coastal areas, which may cause flooding through groundwater inundation (*29*).

In the interest of developing a more comprehensive understanding of the state of global groundwater, we synthesize aspects of the changing nature of groundwater in the global water cycle over recent decades resulting from climate change and other anthropogenic activities. First, we discuss alterations to groundwater systems driven by climate change, including shifts in groundwater recharge and variations in groundwater flow systems in glacierized and permafrost areas. Then, we review other anthropogenic activities that lead to changes in groundwater levels, storage, and regional groundwater flow regimes. Finally, we evaluate the contribution of groundwater to sea level rise and groundwater inundation in coastal areas induced by sea level rise. We acknowledge that human activities also affect groundwater quality but a thorough discussion of groundwater quality changes is beyond the scope of this Review.

Groundwater changes driven by climate change

Effects on groundwater recharge variability

Groundwater recharge is affected by climate variability and change (*30*, *31*). Climate change affects groundwater resources by changing precipitation, evapotranspiration (ET), recharge, and pumpage (*7*, *32*). On a global scale, modern global mean groundwater recharge fluxes are estimated to be at least ~12,000 to ~17,000 km^3 per year (*33–36*). However, recharge rates vary substantially across different regions. Fig. 2A shows simulated mean annual groundwater recharge between 1960 and 2010 modeled by PCR-GLOBWB and considering lateral groundwater flow (*37*). A nonlinear relationship is found between precipitation and groundwater recharge in some regions, with wetter regions having higher recharge than drier areas (*38*). At the global scale, the effects of precipitation change on global average groundwater recharge may be insignificant. Higher precipitation (and recharge) in some areas may be offset by lower precipitation (and recharge) in other areas, leading to relatively small changes in interannual groundwater recharge rates at the global scale but large changes at the local scale (*31*). Both increasing and decreasing trends in groundwater recharge have been found in response to climate change (*14*).

Increases in recharge projected in some areas have been attributed to projected increases in precipitation in regions such as the Upper Colorado River Basin in the United States (*39*) and to increasing intensity of precipitation in regions such as Indonesia and East Africa (*14*, *38*). Increases in induced recharge may also be caused by groundwater overexploitation (*30*). Groundwater withdrawals vary over time with climate extremes, with more withdrawals during droughts and less withdrawals during wet periods (*30*). Declines in groundwater recharge are projected in some tropical and temperate climate regions (*14*, *40*), such as much of the western United States (*41*). An average decline of 10 to 20% in total recharge is estimated for some aquifers in the southwestern United States (*41*). Climate models

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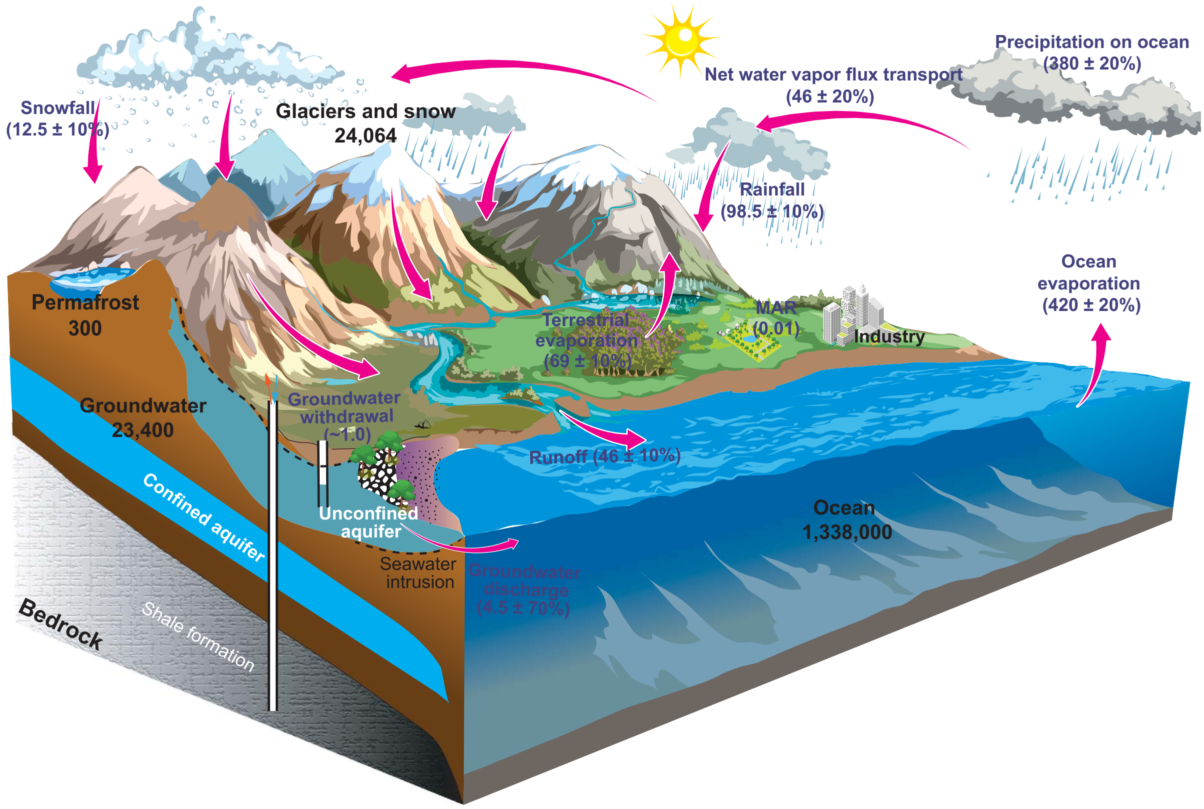

Fig. 1. Global hydrological cycle with its components. The global water fluxes (×1000 km^3 per year) in brackets and water storage (×1000 km^3) were obtained from previous studies (*9*, *36*). The upward arrows show annual evaporation from the ocean and terrestrial evapotranspiration. Global groundwater withdrawal is set at 1000 km^3 per year based on data from 2010 in the literature (*21*). Antarctica was not included in the terrestrial water balance. [Adapted from EreborMountain/Shutterstock]

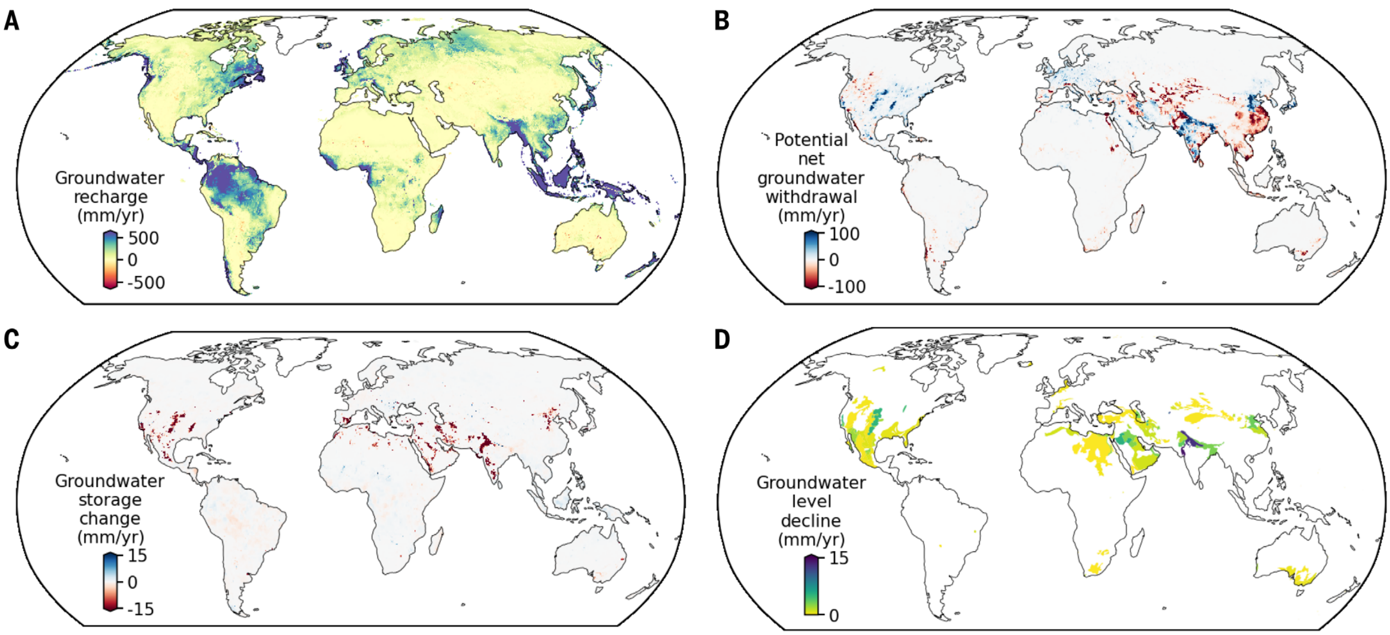

Fig. 2. Groundwater recharge, withdrawal, water level decline, and storage changes. (**A**) Mean annual groundwater recharge from 1960 to 2010 modeled by PCR-GLOBWB coupled with MODFLOW (*37*). Positive values indicate groundwater recharge and negative values indicate capillary rise. (**B**) Mean annual potential net groundwater withdrawal from 1980 to 2016 simulated by WaterGAP 2.2d (*44*). Negative values indicate an increase in groundwater storage caused by surface water irrigation whereas positive values indicate a net removal of groundwater from aquifers due to human water use. (**C**) Annual groundwater storage change rate from 1980 to 2016 modeled by WaterGAP 2.2d (*44*). (**D**) Annual averaged decline in the groundwater level in the world's major aquifers from 1990 to 2014 simulated by PCR-GLOBWB 2 run coupled with MODFLOW (*101*).

project that droughts will become more frequent and intense in California, decreasing recharge and increasing demand for groundwater (*42*). However, considerable uncertainty exists in some of these climate projections.

Surface water irrigation can increase groundwater recharge and replenish aquifers from irrigation return flows (*40*, *43*, *44*). Inefficient surface water irrigation will increase groundwater recharge and storage (*45*). Canal leakage and return flow are the main pathways for increased groundwater recharge from surface water irrigation. Groundwater storage in the Indo-Gangetic Basin increased by ~420 km^3 during the 20th century before large-scale groundwater withdrawal began in the late 1990s and early 2000s (*46*). Leakage from surface water irrigation increased groundwater storage by ~20 km^3 in the Columbia Plateau in the northwestern United States between ~1940 and ~1970 (*45*). Previous studies estimated that 10 to 50% of total irrigation becomes irrigation return flow (*47*); the latter can be reduced with more efficient irrigation schemes such as drip rather than flood irrigation (*48*).

Uncertainty in recharge projections arises from several sources, including uncertainty in changes in future precipitation rates and, critically, intensities (*7*, *40*, *41*). Annual and seasonal precipitation and temperature are identified as some of the most important factors in predicting spatial variation in groundwater recharge (*31*). Considerable uncertainties in future precipitation result in large uncertainties in projected groundwater recharge (*7*). Groundwater recharge is affected by rainfall amount and intensity (*38*, *40*). Regions that experience increases in rainfall intensity may experience increases in groundwater recharge (*12*, *40*). However, many predictions of future changes in precipitation frequency and intensity are highly uncertain. Current representations of hydrological processes and groundwater in global hydrological models may also lead to large uncertainties in the projected groundwater recharge (*14*). Incorporation of the impact of the changing climate and atmospheric CO_2 levels on vegetation in global hydrological models can lead to variations of 100 mm per year in simulated groundwater recharge (*14*). Regionally, the predominant sources of uncertainty may stem from selection of global climate models and emissions scenarios (*49*).

Increases in groundwater contribution to streamflow due to glacier retreat

Glacial meltwater has been identified as an important source of aquifer recharge in glacierized catchments (*50*). A portion of glacial meltwater infiltrates and recharges groundwater; groundwater then discharges farther down-gradient to streams (Fig. 3A) (*51*). For example, in the rapidly retreating Virkisjökull glacier in southeastern Iceland, >25% and often >50% of the groundwater is recharged from glacial meltwater in summer (*52*). In the Upper Indus River Basin, ~44% of annual groundwater recharge is derived from glacial meltwater (*53*).

Groundwater in glacierized catchments contributes substantially to river discharge. In Nepal, groundwater flowing through fractured basement aquifers contributes ~66% of annual river discharge, which is six times higher than the contribution from glaciers and snow melt (*54*). The percentage of river discharge derived from groundwater can be >90% (*55*). During dry periods and winter, groundwater may be the main source of river discharge, with contributions of 50 to 90% (*56*). In the Shullcas watershed in central Peru, a typical proglacial watershed, groundwater provides ~70% of the dry season streamflow (*57*). These examples highlight the importance of groundwater in sustaining streamflow in mountainous areas.

Accelerating glacier retreat may threaten the sustainability of water resources in mountainous areas (*57*); however, groundwater in high mountain areas may provide some resilience to glacier retreat (*19*). Groundwater storage in glacier forelands can buffer streamflow changes (*52*). The stored groundwater is released during dry seasons and compensates for high variability in glacial meltwater and sustains streamflow (*58*). Climate change has induced substantial glacier retreat in recent decades, with glaciers retreating in High Mountain Asia and many of the world's other

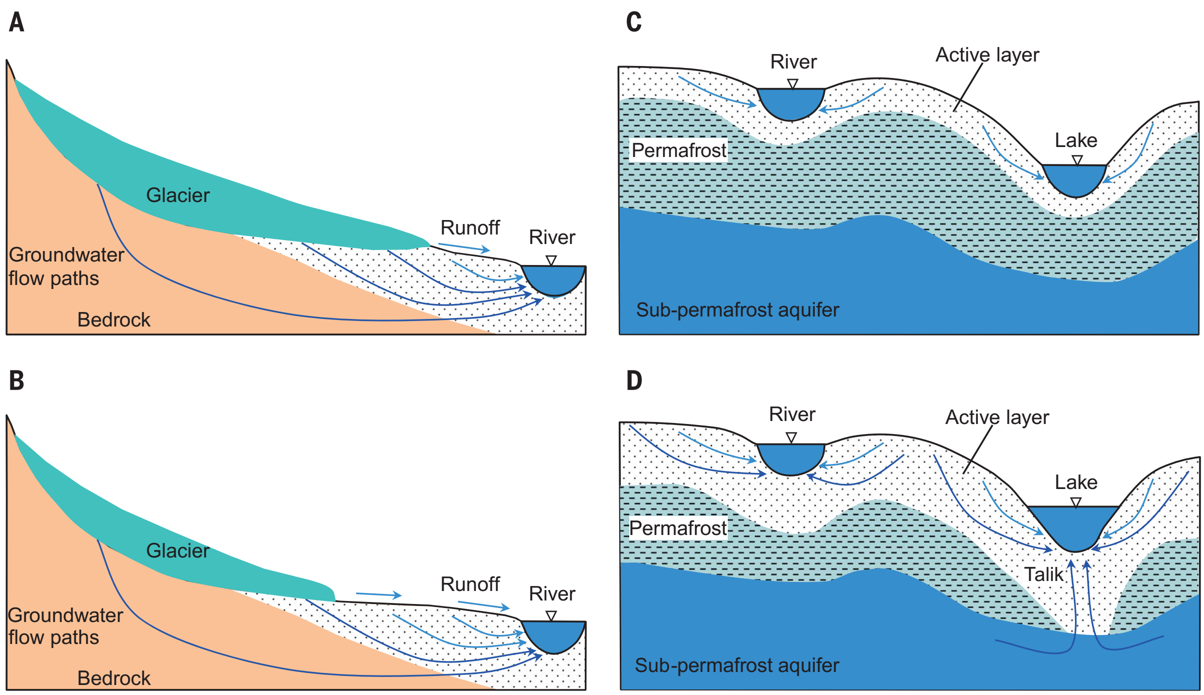

Fig. 3. Schematics of groundwater flow systems in glacierized catchments and permafrost areas. (**A**) and (**B**) Groundwater flow system in a glacierized catchment before and after glacier retreat (A) and (B), respectively (*61*). The blue curves with arrows show the groundwater flow from subglacial meltwater recharge. (**C**) and (**D**) Groundwater flow system in a permafrost area before and after climate warming (C) and (D), respectively (*78*, *79*). The blue arrows in (D) show the enhanced groundwater flow.

high mountain areas (*15*). Global projections suggest that glaciers will lose ~20 to ~50% of their mass by 2100 relative to 2015 (*59*). In the Shullcas watershed in Peru, glaciers are projected to disappear entirely by 2100; however, the relatively consistent groundwater discharge to rivers is expected to compensate for the reduction in glacial meltwater (*57*). Continued future climate change may further decrease glacial meltwater contributions to rivers and some stream sources may undergo a progressive shift toward snow melt and groundwater (Fig. 3B) (*60*).

As climate warming continues, many debris-covered glaciers will transform into rock glaciers, which are poorly sorted, angular rock debris with ice (*61*). Groundwater stored in rock glaciers discharges to streams through springs (*61*, *62*). In the Canadian Rockies, groundwater discharge from one rock glacier spring accounts for 50% of streamflow during summer and up to 100% during winter (*63*). Continued climate warming may lead to the thawing of ice in rock glaciers. Although streamflow may initially increase as a result of ice melting in rock glaciers (*62*), after the volume of stored ice has declined, snowmelt and rainwater formerly flowing on the ice surface may infiltrate into the rock glacier matrix and flow out of the basin as groundwater (*62*) (Fig. 3B).

Rock glaciers, talus, moraines, and alpine meadows are typical to alpine aquifers (*64*). Alpine aquifers can store large volumes of groundwater, which is vital in sustaining baseflow in rivers during low-flow seasons (*64*). In the Canadian Cordillera, which is experiencing glacier retreat, minimal reductions in winter streamflow have been observed in 17 rivers, indicating that groundwater storage in alpine headwater aquifers supports streamflow during the low-flow season (*64*). The high hydraulic conductivities of these alpine aquifers allow rapid infiltration of rainwater and snowmelt to unconfined aquifers above bedrock surfaces (*63*); these aquifers can then provide steady discharge to rivers for many months (*64*, *65*). A large amount of groundwater stored in these aquifers sustains river runoff and stabilizes catchment outflow, which may affect catchment responses to climate change (*65*).

Groundwater flow enhancement by permafrost thaw

Permafrost underlies 14 to 16 million km^2 of the Earth's exposed land surface (*66*), with a mean active layer thickness of ~0.8 m in the High Arctic and ~2.3 m in the alpine and high-plateau regions (*67*). The observed permafrost temperatures have increased continuously over the past few decades (*17*, *68*). Permafrost thaw and active layer thickening occur throughout cold regions globally (Fig. 3, C and D); the latter has been observed since the 1990s (*68*), and in the Russian Arctic the active layer thickness increased by 0.4 m between 1999 and 2019 (*68*). In the Tibetan Plateau, the active layer thickness increased at 19.5 cm per decade from 1980 to 2018 (*69*), and the permafrost area decreased by ~1500 × 10^3 km^2 during the past half century (*70*).

Thawing permafrost increases groundwater storage, deepens groundwater flow pathways, and augments groundwater discharge to streams (Fig. 3, C and D) (*18*, *71*, *72*), especially during low-flow seasons (*73*). The permafrost area in the Yangtze River source region decreased by ~8000 km^2 between 1962 and 2012, increasing groundwater storage at a rate of 1.6 km^3 per year (*74*). In the Yukon River basin, long-term (>30 years) observations indicate a 7 to 9% increase in groundwater discharge to streamflow per decade (*18*). Thawing permafrost and thickening of the active layer can augment baseflow by enhancing groundwater flow pathways and releasing groundwater from storage to streams (*75*–*77*). Thickening of the active layer can eventually lead to the formation of large taliks (unfrozen zones in permafrost), plausibly increasing infiltration rates, subsurface storage volumes, and flow depths that alter groundwater flow pathways (Fig. 3, C and D) (*78*, *79*), increasing groundwater discharge to streams through baseflow (*72*). Progressive permafrost thaw facilitates shallow groundwater flow systems whereas complete permafrost thaw creates new deep groundwater flow systems (*73*). Thawing permafrost also increases hydrologic connectivity and linkages between surface water and groundwater (*77*).

Vertical talik expansion enhances regional groundwater circulation (*76*, *79*). When a closed talik degrades to an open talik (i.e., a talik completely penetrates the permafrost), a pathway is created for groundwater flow (*78*). Open taliks connect shallow groundwater in the active layer to the aquifer below the permafrost, serving as vertical conduits for groundwater flow (Fig. 3D), thus enhancing regional groundwater circulation and discharge (*79*). Open taliks enhance surface water–groundwater interactions and groundwater flow converges at the talik (*78*, *80*). Open taliks allow migration of relatively warm groundwater from above or geothermally warmed groundwater from below, thus accelerating permafrost thaw and expanding the talik network (*81*).

As global warming persists in the coming decades, permafrost is projected to continue thawing (*82*). Over 40% of permafrost area may disappear if the climate is stabilized at 2°C above preindustrial levels (*82*). The low permeability of permafrost generally provides a hydraulic barrier that reduces rainfall and snowmelt infiltration (*83*). Where permafrost is discontinuous, rainfall and snowmelt can infiltrate and recharge groundwater, flow within the groundwater system, and finally discharge to streams, providing stable baseflow during winter and dry periods (*84*). Enhanced infiltration, groundwater storage, and groundwater flow indicate an expanding role for groundwater in the high-latitude hydrological cycle (*85*). Continued permafrost degradation may exacerbate regional ecological challenges, including a reduction in soil water availability, vegetation degradation or greening, and land desertification (*86*). It is crucial to recognize the intricate interdependencies between the permafrost thermal regime and vegetation, as the impact of vegetation on permafrost degradation is complex (*68*, *86*).

Substantial increases in groundwater discharge to streams induced by permafrost thaw are likely to occur in the next few centuries (*73*, *87*). An increase of 2°C in the mean annual surface temperature of the Tibetan Plateau could increase groundwater discharge to streams by a factor of three (*88*). The increase in runoff is caused by infiltrated water flowing through the subsurface and discharging to rivers during periods of flow recession (*71*). In catchments with ice-rich permafrost, excess ground ice provides large quantities of potential meltwater for groundwater flow (*87*).

Groundwater changes driven by other anthropogenic activities

Groundwater withdrawal

Groundwater is pumped out of many aquifers globally (*89*, *90*). As an essential water source for humans, groundwater withdrawal accounted for an estimated ~22% of total water withdrawal in 2000 according to global hydrological models (*34*) and ~26% in 2010 according to national and international databases (*91*). Groundwater is withdrawn from both unconfined and confined aquifers (Fig. 4, A and B). Global groundwater withdrawal increased from ~310 ± 37 to 460 km^3 per year in 1960 (*4*, *92*, *93*), to ~570 to 790 ± 30 km^3 per year in 2000 (*21*, *33*, *34*), and then to ~1000 km^3 per year in 2010 (*21*). Fig. 2B shows the mean annual potential net groundwater withdrawal from 1980 to 2016 simulated by the global hydrological model WaterGAP 2.2d (*44*). Although global groundwater withdrawal has increased from 1960 to the present, groundwater withdrawal has stabilized during recent decades in countries such as the United States, China, Pakistan, and Iran (*91*, *94*). Large groundwater withdrawals have caused substantial declines in global aquifer storage (Fig. 2C) (*6*, *95*, *96*) and groundwater depletion may account for ~15% of total groundwater withdrawal (*97*, *98*). The remaining 85% of groundwater withdrawal is linked to surface water capture, reduced evapotranspiration, and decreased discharge (*97*, *98*). Groundwater withdrawal has resulted in substantial groundwater level declines in many areas in recent decades, such as parts of the US High Plains aquifer, the

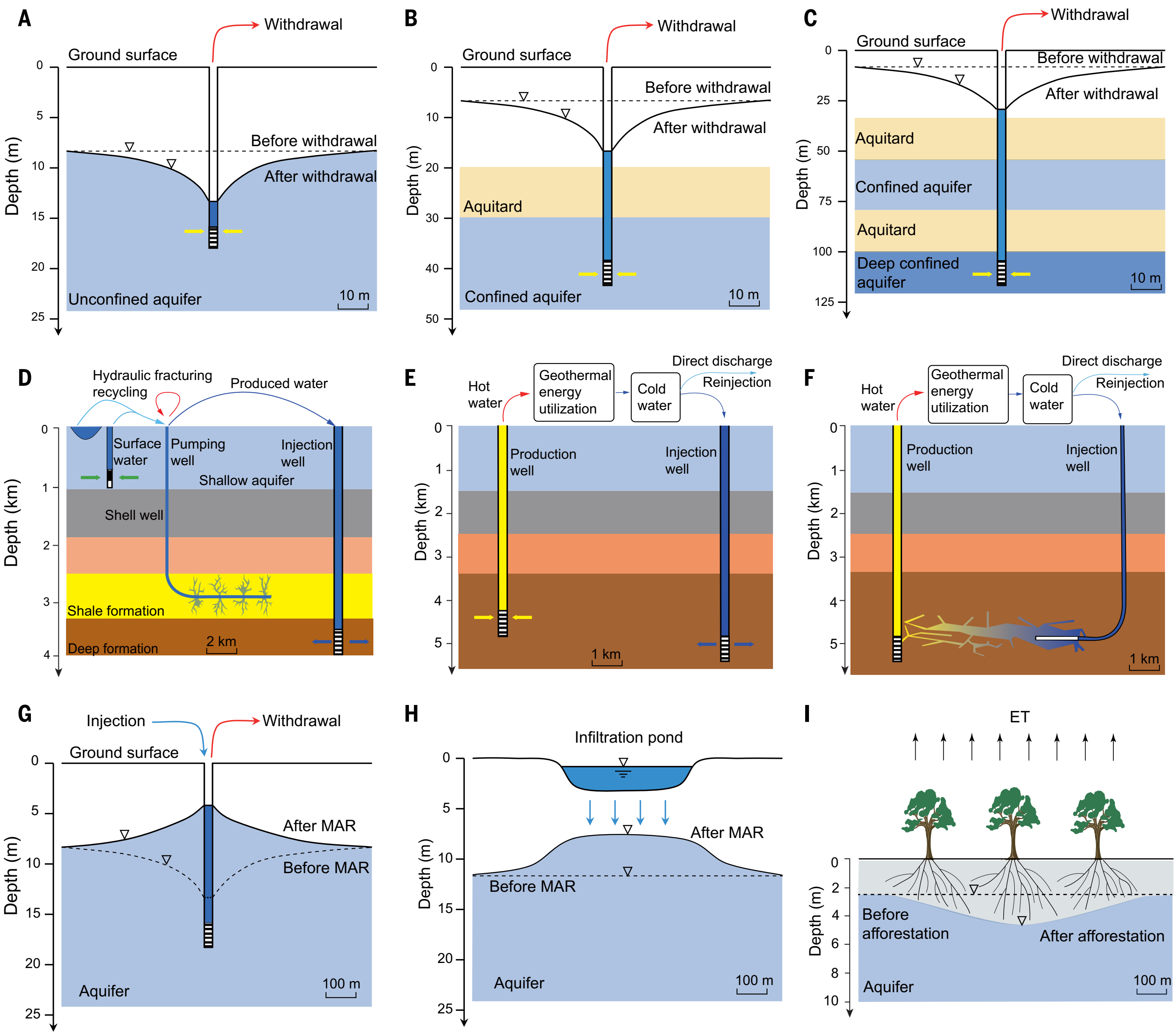

Fig. 4. Schematics of different types of groundwater withdrawal and recharge. Groundwater withdrawal in an (**A**) unconfined aquifer, (**B**) confined aquifer, and (**C**) deep confined aquifer. (**D**) Schematics of shale gas development with hydraulic fracturing of a horizontal well (*117*, *118*). (**E** and **F**) Schematics of different geothermal systems: (E) two-well circulation system and (F) enhanced geothermal system (*23*, *129*). (**G** and **H**) Schematics of MAR: (G) Aquifer storage and recovery, in which water is injected into the aquifer for storage and recovery using the same well; (H) Infiltration ponds, in which water infiltrates from a constructed pond into an unconfined aquifer for storage and recovery (*140*). (**I**) Water table before and after afforestation. ET, evapotranspiration.

North China Plain, and the Indo-Gangetic Basin (Fig. 2D) (*32*, *46*, *99*–*101*).

Groundwater depletion is often caused by withdrawals for irrigation (*5*, *99*). Global annual irrigation water use was estimated to be 960 ± 130 km^3 per year from 2011 to 2018 (*102*). Groundwater accounts for 45 to 50 and 60% of irrigation in India and the United States, respectively (*5*, *99*). Global groundwater depletion was estimated to be 56 km^3 per year from 1960 to 2000 and 113 km^3 per year from 2000 to 2009 according to WaterGAP (*43*) and 137 km^3 per year from 1960 to 2010 according to PCR-GLOBWB (*93*). Estimates of cumulative global groundwater depletion between 1960 and the early 21st century range from 2000 to as much as ~27,000 km^3 (*93*, *103*), highlighting the substantial uncertainty in cumulative groundwater depletion estimates. Groundwater depletion varies substantially across different regions (*21*); depletion estimates include 8 ± 3 km^3 per year from 2000 to 2012 in the transboundary Indo-Gangetic Basin (*104*), ~4 km^3 per year from 2003 to 2010 in the California Central Valley (*105*), and ~6 km^3 per year from 1945 to 2020 in the North China Plain (*106*).

Groundwater with mean renewal times surpassing human timescales (i.e., 100 years) is globally widespread and has been termed "nonrenewable" in some works (*21*, *107*). Pumpage of this old groundwater is especially common when wells tap deep aquifers (Fig. 4C). An estimated ~20% of global gross irrigation water demand was derived from this old groundwater in 2000 (*4*). Groundwater that was recharged by precipitation that fell before the Holocene (~12,000 years ago) is termed fossil groundwater (*7*, *9*, *108*). A synthesis of ~6500 wells globally shows that fossil groundwater dominates storage at depths of ≥ ~250 m (*108*). In the US High Plains Aquifer, the estimated depletion of fossil groundwater—much of which was recharged during the past 13,000 years—was 330 km^3 from the 1950s to 2007 (*5*). Groundwater overexploitation in some aquifers leads to permanent depletion of water resources, sometimes referred to as groundwater mining (*109*). In the United States, the proportion of newly drilled wells that are sufficiently deep (200 ± 100 m) to tap fossil aquifers has grown in recent decades, although this deep drilling is not necessarily associated with depletion (*110*).

Groundwater withdrawal is expected to increase under different future climate change scenarios (*21*, *111*, *112*). By 2050, the estimated global groundwater withdrawal rate is projected to be ~1250 ± 118 km^3 per year, and the depletion rate is estimated to be ~300 ± 50 km^3 per year (*21*, *111*). By 2099, the projected global groundwater withdrawal is ~1600 ± 130 km^3 per year, and the depletion is ~600 ± 85 km^3 per year (*92*). Declining water levels may result in wells drying up, meaning deeper wells must be drilled to supply water (*113*). If global groundwater levels were to decline by only a few meters, millions of wells would be at risk of running dry (*114*). Deep fresh groundwater will become a strategic resource in areas with high extraction and low recharge rates (*113*). However, drilling deeper wells is an unsustainable stopgap measure for addressing groundwater depletion (*113*).

Groundwater pumped from aquifers participates in the global water cycle by discharging to rivers and providing water for evapotranspiration (*33*, *99*). In regions with groundwater-fed irrigation, increased groundwater use may cause higher evapotranspiration (*102*), potentially leading to higher precipitation downwind and thus augmenting river discharge (*40*). Irrigation in California's Central Valley strengthens the regional water cycle by an estimated ~15% increase in summer precipitation and a nontrivial increase in Colorado River streamflow (*115*). Large groundwater withdrawals can modify natural groundwater flow systems. Groundwater discharges to streams—which are vital to sustaining streamflow especially during dry seasons and droughts—may decline or even stop flowing, springs may dry up, and streamflow may decrease (*2*, *112*). With greater groundwater withdrawals, particularly in areas with dry climates, it is likely that there will be more ephemeral and losing rivers (streams with water levels higher than those in adjacent wells) that can seep into underlying aquifers (*100*, *116*). More studies are needed to evaluate changes to global hydrological cycling induced by increased groundwater withdrawals as well as to assess the role of capture in groundwater resources in different regions.

Unconventional oil and gas production

To enable unconventional oil and gas production from low-permeability source rocks such as shale, coal, or tight sandstone formations, hydraulic fracturing is widely used (Fig. 4D) (*117*, *118*). During hydraulic fracturing, high-volume, high-pressure fluids, chemical additives, and proppants are injected into the low-permeability shale and tight rocks to fracture and maintain open fractures in the rocks (*117*, *119*, *120*). Horizontal drilling and hydraulic fracturing allows for large quantities of gas or oil to be extracted from these rocks (Fig. 4D). From 2009 to 2017, 1.8 km^3 of water was used to fracture ~73,000 wells with a total lateral length of 134,000 km in the United States (*22*). Annual water use for hydraulic fracturing for major plays in the United States has increased rapidly since 2009 (*22*, *121*). Groundwater was the primary water source (~13,000 wells) for hydraulic fracturing from 2010 to 2019 for the Permian Basin in the United States (*121*). Future increases in unconventional oil and gas production would require larger quantities of water for hydraulic fracturing, which would also lead to larger volumes of produced water (*120*).

Produced water is coproduced with oil and gas over the life of a well and is mostly comprised of formation water (*122*, *123*). The volume of produced water is estimated to vary widely from 1720 to 50,000 m^3 per well, with 1720 to 14,320 m^3 per well for the major US unconventional plays, 10,000 to 20,000 m^3 per well during the first year of production for China, and 10,000 to 50,000 m^3 per well for Canada (*118*, *120*). Common methods for produced water management include deep underground injection, reuse for hydraulic fracturing, and surface discharge. Part of the produced water is reused for hydraulic fracturing and the percentage of water used for the latter derived from recycling tends to increase over time (Fig. 4D) (*22*, *118*, *122*). For the Marcellus Shale in the United States, 13% of the produced water was recycled from 2000 to 2010; this percentage had increased to 56% by 2011 (*122*). Deep underground injection is the primary method for produced water management (Fig. 4D) (*119*, *122*). Most of the produced water in the United States is managed by deep underground injection (*22*, *122*).

In semiarid regions and/or areas with high groundwater consumption, the use of groundwater for drilling and hydraulic fracturing may change local water availability or lead to water stress (*22*, *124*, *125*). Globally, 20% of shale deposits are located in regions with groundwater depletion (*125*). In the United States, nearly half of shale wells are distributed in water-scarce basins, in which unconventional wells increased water use (*22*, *124*). The withdrawal of groundwater for shale oil or gas development may also lead to declining water levels and decrease the contribution of baseflow to streams (*22*, *121*, *126*). For the Eagle Ford play and Permian basin in the United States, a total of ~11,000 water wells were drilled to meet water demands for hydraulic fracturing from 2009 to 2017 (*22*). Water levels declined more considerably in confined aquifers in the Eagle Ford play (6 to 18 m per year over a ~5-year period) than in unconfined aquifers (*22*). From 2009 to 2013, the use of groundwater for hydraulic fracturing in the Eagle Ford play resulted in an estimated local drawdown of ~30 to 60 m in ~6% of the western play area (*126*).

Regional groundwater flow regimes may be modified by unconventional oil or gas production. When groundwater is used for hydraulic fracturing, large volumes of groundwater are generally pumped out from shallow aquifers. Shallow groundwater is injected into shale layers during hydraulic fracturing and part of it remains in the shale layer. The produced water is then injected into deep underground geologic formations. The withdrawal and injection of groundwater leads to the redistribution of groundwater at different depths. Upward hydraulic gradients may be caused by injection that could potentially result in upward fluid leakage into shallow aquifers (*127*). Hydraulic fracturing also provides additional pathways for groundwater flow. Additionally, abandoned wells can provide potential conduits for produced water, and groundwater may flow from one aquifer to another (*121*, *128*).

Geothermal energy exploration

Geothermal energy can be used for either geothermal power generation or direct utilization (*129*). Geothermal power generation has increased significantly worldwide in recent decades (*23*, *130*). From 2010 to 2014, at least 2200 wells were drilled in 42 countries for both direct utilization and power generation, a 6.2% increase compared with 2005 to 2009 (*131*). From 2015 to 2019, at least 2647 wells were drilled by 42 countries for both direct utilization and power generation, with an additional ~20,000 shallow heat pump wells up to 100 m deep (*132*). Geothermal direct utilization worldwide increased from 71 GWt in 2014 to 108 GWt in 2019 (*131*, *132*). The number of countries with direct utilization of geothermal energy increased from 28 in 1995 to 88 in 2019, including China, the United States, Sweden, Germany, and Turkey (*132*).

The utilization of geothermal energy can be realized by pumping hot groundwater out of a hydrothermal system. Intensive withdrawal of deep thermal groundwater is needed during geothermal energy production. After geothermal energy utilization, the cold water is either reinjected deep underground or discharged directly to the surface (Fig. 4E). For a single-well extraction system, hot groundwater was pumped out and then released on the surface after use (*133*). The ratio of reinjected mass to produced fluid can vary from 5 to 100% (*23*). The distance between the production and reinjection zones ranges from 0.1 to 6.0 km, with an average value of 1.3 km (*23*). Sources of water used for reinjection include produced and surface water such as waste-, rain-, stream-, lake-, and groundwater (*23*). Enhanced geothermal systems use engineering strategies to enhance geothermal energy production, in which hydraulic fracturing is utilized to improve rock permeability and the injected water is heated by the rock (*129*, *134*). The heated water is pumped out by the production well and the cold water is reinjected (Fig. 4F). Throughout many stages of enhanced geothermal systems, a substantial amount of water is introduced into the deep subsurface, including water from well drilling, hydraulic fracturing, and fluid circulation, in addition to water lost during the recovery process (*129*).

As geothermal production and injection wells are generally several kilometers deep, groundwater withdrawal and injection may cause deep groundwater redistribution among different formations, perturbing local water cycling to some degree (*135*). Injection can also lead to elevated pore pressure, which may reactivate faults and cause new thermal fractures (*134*, *136*, *137*), thus providing new paths for deep groundwater flow. At the Geysers geothermal field in the United States, injected water can migrate >3 km below the injection point due to a hydraulically conductive fracture network (*136*). At the Nesjavellir geothermal field in Iceland, the injected fluid flowed through faults from the injection zone to the northeast (*138*). Intensive withdrawal of deep thermal groundwater can decrease the artesian pressure in deep fractures and allow shallow groundwater to flow into these deep fractures (*135*). In some geothermal fields, excessive withdrawal of geothermal fluid has resulted in sea or lake water intrusion when a sea or lake is nearby (*23*). Additional water may also be injected into geothermal systems to sustain production rates and maintain reservoir pressures (*23*, *139*).

Managed aquifer recharge

Managed aquifer recharge (MAR) refers to intentionally recharging and storing water in aquifers for subsequent recovery and various beneficial uses (*24*, *140–142*). As a means of adapting to climate change and land use change and realizing sustainable water management, MAR has been implemented in many regions globally (*143*), including Europe, Australia, North and South America, Africa, and South Asia (*30*, *141*, *144*). MAR has also been implemented in mines to preserve aquifers, manage surplus water, or adhere to licensing (*145*). Effective MAR means that both water quantity and quality are managed effectively and is a water management strategy that is becoming increasingly important (*24*). There are ~1200 MAR sites in 62 countries (*143*). MAR has increased by 5% per year since the 1960s (*24*). The average MAR volume increased from 1.0 km^3 per year in 1965 to 10 km^3 per year in 2015, representing ~1% of global groundwater withdrawal in 2015 (*24*); however, it can be important for alleviating regional water stress (*98*). MAR is projected to exceed 10% of global groundwater extraction as MAR techniques become more advanced (*24*). MAR as a percentage of groundwater use varies significantly for different continents, from 0.4% in Africa to 9% in the Middle East (*24*, *142*).

MAR refers to a suite of methods that can be used to maintain and enhance groundwater systems under climate change and groundwater overexploitation (*24*, *146*). MAR projects have various goals, such as raising groundwater levels, increasing groundwater storage, improving groundwater quality, preventing saltwater intrusion, and meeting irrigation demand (*24*, *143*, *146*). Different water sources have been used for MAR, including surface water (rivers and lakes), stormwater, treated wastewater, desalinated water, rainwater, and fresh and brackish groundwater from other aquifers (*141*, *144*, *147*). Surface waters such as river and lake water are the dominant sources of MAR (*142*, *144*). There are many types of MAR methods, including infiltration basins, percolation tanks, bank filtration, recharge wells, and agricultural MARs (*140*, *141*, *148*) (Fig. 4, G and H). Depleted aquifers provide additional subsurface reservoir storage capacity for MAR in many regions, estimated at ~1000 km^3 in the United States, exceeding the surface reservoir storage capacity (*98*).

MAR buffers against the adverse impacts of climate extremes or change (*142*) and groundwater overexploitation (*149*). MAR can be used to enhance resilience to drought by storing excess surface waters and recycled water (*146*). Additional water is recharged during flooding or wet periods for subsequent abstraction during drought or dry periods (*142*, *146*, *149*). Depleted aquifers can be used to store water by recharging groundwater with surface water through MAR (*147*, *150*). In semiarid areas where groundwater is either overexploited or saline, MAR has the potential to store excess runoff in aquifers (*140*). Stormwater or floodwater can drain into aquifers through infiltration basins, wells, or sumps to reduce flood and drought risks and then reuse this water for drinking or irrigation purposes (*140*, *151*). Guidelines and regulations are vital to implementing MAR safely and sustainably (*152*).

Afforestation

Afforestation can potentially increase annual evapotranspiration (Fig. 4I) while reducing annual streamflow. Global tree cover increased by 2.2 million km^2 from 1982 to 2016 (*153*). Climate simulations suggest that tree plantations can increase summer evapotranspiration by more than 0.3 mm per day (*154*). Large-scale tree restoration has been found to increase terrestrial evapotranspiration by 1.2% and increase terrestrial precipitation by 0.7% due to recycling of increased evaporation (*155*). Large-scale tree plantations may lead to groundwater declines where the enhanced evapotranspiration rates reduce recharge (*25*, *156*). However, divergent impacts of tree restoration on streamflow have been found (*155*, *156*). Some rivers experienced a decrease in streamflow by 6% as a result of enhanced evapotranspiration whereas for other rivers, the greater evapotranspiration is counterbalanced by enhanced moisture recycling (*155*).

Afforestation can cause declines in the water table (Fig. 4I) as well as reductions in groundwater recharge, effective infiltration, soil moisture, and baseflow to streams. Afforestation may lead to water table declines in arid and semiarid areas of 0.5 to 3.0 m from 1952 to 2011 (*25*, *157*). Compared with grasslands, groundwater recharge decreased by 3 to 7% for deep-rooted forests (*158*). Much greater reductions in recharge of 33 to >90% were found in forests related to surrounding bare sandy soil in semiarid areas (*159*). Groundwater recharge is reduced as a result of increased transpiration and interception (*160*). Increased tree cover reduces soil moisture (*161*); for example, revegetation of a 16,000 km^2 area in the Loess Plateau in China decreased soil moisture by ~2.4 mm per year and reduced runoff by ~0.5 mm per year from 2000 to 2010 (*162*). As forest plantations increase evapotranspiration (*162*), groundwater discharge to streams (baseflow) tends to decline, especially in drylands or during dry seasons (*25*, *156*).

Land reclamation and urbanization

Coastal groundwater flow systems can be modified by land reclamation and urbanization. During urbanization of coastal areas, land reclamation from the sea and high-rise building construction with deep foundations are two common measures implemented to meet the growing demand for land (*26*, *163*). Land reclamation in coastal areas is practiced worldwide (*164*). Large-scale land reclamation can change the regional groundwater regime by increasing groundwater levels and altering or slowing seaward groundwater discharge (Fig. 5A) (*164*, *165*). Locally, seaward groundwater discharge may increase as a result of additional recharge in reclaimed land (*163*). The saltwater-freshwater interface may also move seaward after land reclamation. The

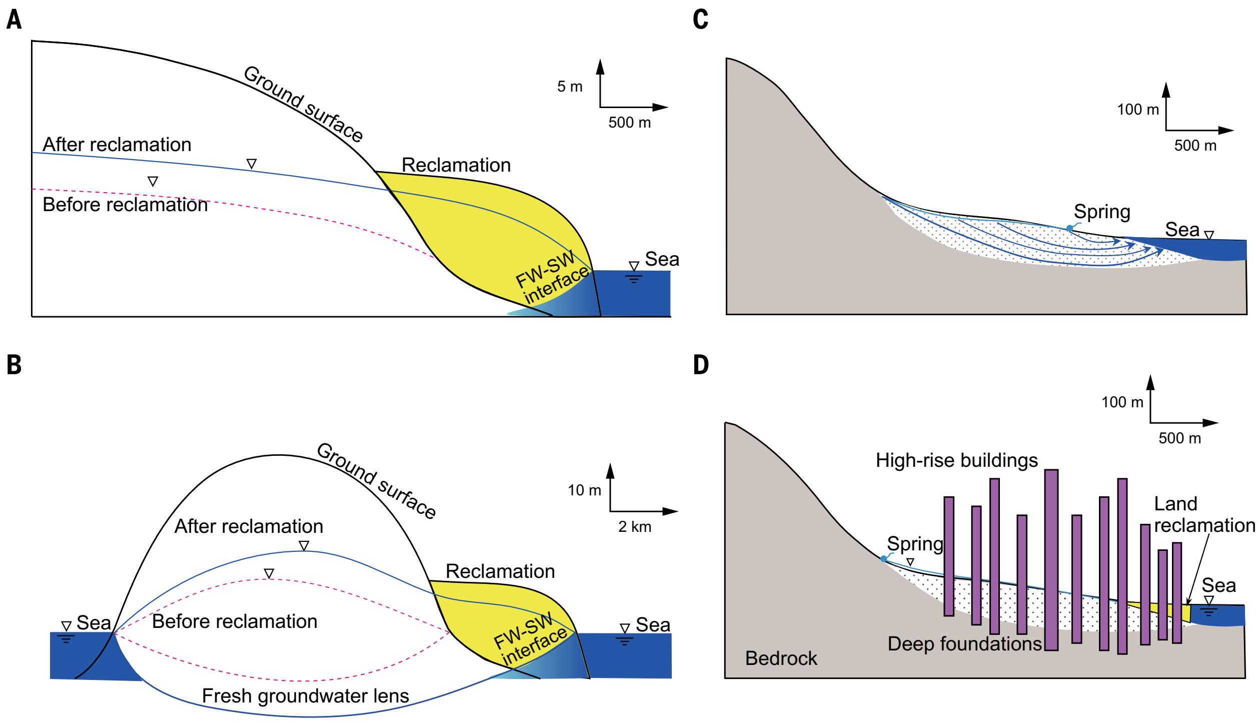

Fig. 5. Groundwater flow system changes caused by land reclamation and urbanization. (**A**) Land reclamation beside a coastal hillside with an unconfined aquifer (*164*, *165*). (**B**) Land reclamation beside an elongated oceanic island with an unconfined aquifer (*164–166*). (**C**) Coastal groundwater flow system before land reclamation and urbanization (*26*, *173*). (**D**) Coastal groundwater flow system after land reclamation and urbanization with deep foundations (*26*, *173*). Curves with arrows show the groundwater flow paths. FW-SW interface, freshwater-saline water interface.

response of a given groundwater system to land reclamation can be a slow process, requiring several decades to reach a new equilibrium (*163*). Land reclamation around an oceanic island can change the groundwater system on the entire island, raising the water table on the island, shifting the water divide toward the reclaimed side, and increasing submarine groundwater discharge on the other side (*164*, *165*). The saltwater-freshwater interface at the reclamation side may also move seaward after land reclamation (Fig. 5B) (*164*, *165*). Lab experiments and numerical modeling indicate that land reclamation can enlarge fresh groundwater lenses by up to 85% in tropical islands (*166*).

Groundwater systems can also be modified by dewatering and underground structures. Construction of high-rise buildings or underground infrastructures usually includes dewatering, deep excavations, and diaphragm walls (*167*). In areas with shallow water tables, dewatering requires pumping large quantities of groundwater (*168*). Artificial recharge beyond the excavation site can mitigate the impacts of dewatering on the foundation stability of neighboring buildings (*167*). Underground structures below the water table impact the groundwater flow system by acting as barriers to flow and altering the groundwater budget (*168–171*). The water table rises up-gradient of the underground structures and falls down-gradient (*169*, *172*). Deep foundations limit groundwater flow, raising the water table and leading to upward groundwater flow in the transition zone between the natural slope and urbanized areas (*26*, *172*, *173*) (Fig. 5, C and D). When permeable natural soils are replaced by much less permeable deep foundations, the hydraulic conductivity of the aquifer system is reduced locally (*26*, *173*).

During urbanization, native surface soils are replaced by impervious surfaces, including roads, foundations, and pavement. These impervious surfaces prevent infiltration, leading to more surface runoff and less groundwater recharge (*171*). However, other studies show that urbanization leads to increased recharge due to rain and runoff infiltration and losses from water supply systems and sewer systems (*174*, *175*).

International food trade

A substantial share of groundwater depletion has primarily resulted from irrigation and an estimated ~11% of groundwater depletion is linked to the international food trade (*176*). The global groundwater depletion embedded in international food trade increased from 18 km^3 per year in 2000 to 26 km^3 per year in 2010 (*176*). "Virtual water trade" refers to exchanges of virtual water (amount of water embedded in a commodity) between different regions or nations through the exchange of physical commodities such as food (*177*). Enhanced international food trade is the main reason for increasing virtual water trade (*177*). At a national scale, groundwater depletion in three major US aquifers (Central Valley, High Plains, and Mississippi Embayment) related to food trade in the United States is linked primarily to domestic food transfers (31 km^3), accounting for 90% of trade-related groundwater depletion, with the remaining 10% accounted for by international exports (*178*). Groundwater depletion linked to domestic trade grew from 26 km^3 in 2002 to 35 km^3 over a decade (2002 to 2012), with a similar rise in international trade (2.7 to 3.7 km^3) (*179*).

Embedded green water (soil moisture) and blue water (surface- and groundwater) exports are projected to more than triple from 2010 to 2100 from ~905 to 3200 km^3 for green water and ~56 to ~170 km^3 for blue water (*27*). To meet future crop demands, international food trade is projected to nearly triple by 2050, including virtual water transfers from water-abundant regions to water-scarce regions (*180*).

Large groundwater volumes embedded in international food trade redistribute groundwater demand globally. Virtual water trading generates a virtual water flux that links water resources used physically in the production area to the consumption area (*181*). Unsustainable irrigation embedded in virtual water trade globally demonstrates a redistribution of irrigation water demand, including groundwater demand (*182*). From 2000 to 2015, an estimated 15% of global unsustainable irrigation was virtually exported (*182*). Studies on changes in the global water cycle should consider both the physical and virtual water cycles (*181*).

Groundwater and sea level rise

Contribution of groundwater to sea level rise

Groundwater withdrawal transfers fresh water from long-term groundwater storage to the active water cycle at the Earth's surface (*7*). Much of the groundwater ultimately returns to the ocean and causes sea level rise, which is particularly important in coastal areas (Fig. 6, A and B) (*28*, *183*). Groundwater withdrawal also causes land subsidence, and coastal land subsidence contributes to relative sea level rise (*184*). From 1900 to 2008, the estimated contribution of cumulative global groundwater depletion to sea level rise was 13 mm (*103*) and ranged from 13 to 19 mm from 1948 to 2016 (*185*). The rate of global mean sea level rise increased from 1.56 ± 0.33 mm per year from 1900 to 2018 to 3.35 ± 0.47 mm per year from 1993 to 2018 (*183*). Similar increasing rates were reported in other studies from 1.7 ± 0.3 mm per year since 1950 to 3.3 ± 0.4 mm per year from 1993 to 2009 (*186*). Estimated contributions of past groundwater depletion to rates of sea level rise range from 0.2 to 0.9 mm per year (*187*, *188*). Global groundwater depletion was estimated to contribute 0.31 mm per year (2000 to 2009) to sea level rise based on WaterGAP (*43*) and 0.40 ± 0.11 mm per year (2000 to 2008) based on in situ measurements (*103*), accounting for ~10% of global mean sea level rise.

Te global mean sea level has been predicted to rise by 0.5 to 1.4 m by 2100 (*29*, *186*), with the contribution of groundwater depletion to sea level rise projected to increase in the future (*111*). By 2050, groundwater depletion has been projected to contribute 0.82 ± 0.13 mm per year to sea level rise (*111*) and the percentages of cumulative contribution of groundwater depletion to global sea level rise range from ~10 to ~27% (*29*, *111*). Groundwater depletion and sea level rise may lead to seawater intrusion into coastal freshwater aquifers which is becoming a critical environmental issue, with ~500 coastal cities experiencing seawater intrusion crises globally (*189*, *190*). Seawater intrusion may become even more challenging to manage because of climate change (*190*).

Groundwater inundation induced by sea level rise

Rising sea levels can cause water tables to rise in unconfined coastal aquifers (*29*, *191*, *192*). This rise can then cause groundwater discharge to surface drainage networks and flooding from below in low-lying coastal areas (Fig. 6, C and D), which is referred to as groundwater inundation (*29*, *192*). In California, areas flooded in this manner are projected to expand ~50 to 130 m inland in response to a sea level rise of 1 m (*192*). In northern California's coastal plains, a 1- to 2-m sea level rise may cause widespread groundwater emergence (*193*). In urban Honolulu, Hawaii, a 1-m sea level rise may inundate an estimated 10% of a 1-km wide coastal zone that is heavily urbanized (*29*). Groundwater inundation alone may increase the area flooded by seawater inundation by a factor of two (*29*). In urbanized coastal areas, dense networks of buried and low-lying infrastructure may lead to thinning and loss of unsaturated subsurface space, which may further magnify the risk of groundwater inundation (*194*). Groundwater inundation caused by sea level rise enlarges the likelihood of groundwater discharge at the surface and accelerates groundwater circulation within the water cycle in coastal areas.

Sustainable use of groundwater resources

Globally, groundwater resources face substantial threats in terms of both their quantity and quality (*21*, *30*). Excessive groundwater withdrawals continue to drive substantial groundwater depletion and the demand for groundwater is projected to rise. Climate warming has led to a diverse array of changes in groundwater recharge across different regions of the world. Other anthropogenic activities are reshaping regional groundwater flow regimes, complicating groundwater storage dynamics, altering groundwater discharge to streams, and redistributing embedded groundwater in the global food supply chain. Groundwater depletion transfers fresh water from long-term storage to the active water cycle, thereby contributing to sea level rise. Moreover, pollution from anthropogenic sources and interactions between surface water and groundwater have led to deterioration in groundwater quality (*195*). Groundwater-dependent ecosystems and geological environments have been severely affected by water table changes or poor groundwater quality (*195*).

Given these challenges, the sustainable use of groundwater resources is a crucial global

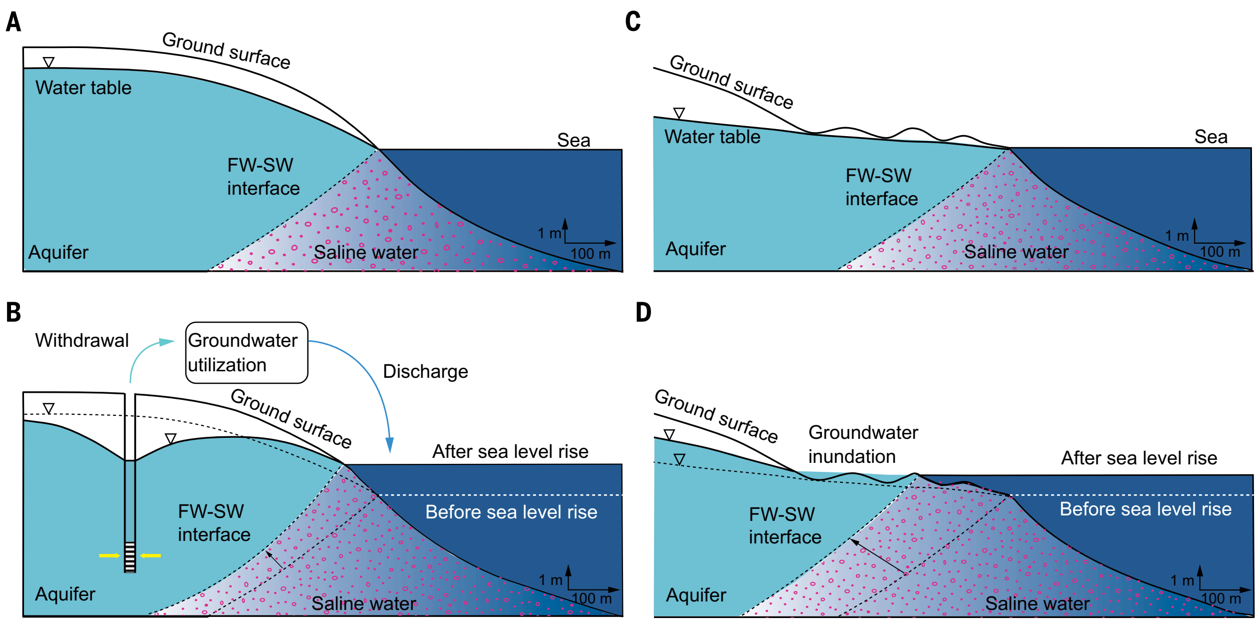

Fig. 6. Schematics of groundwater withdrawal, sea level rise, and inundation. (**A** to **B**) Contribution of groundwater withdrawal to sea level rise (*28*, *187*). (**C** to **D**) Groundwater inundation caused by sea level rise (*29*). FW-SW interface, freshwater-saline water interface.

concern. In planning for a more sustainable future for water in an increasingly interconnected world, groundwater resources should be considered from both regional and global perspectives, especially in the case of large, transboundary groundwater systems (*196*). As global changes continue to affect these resources, it is imperative to manage groundwater and surface water as a single resource (*98*). Additionally, ensuring food and water security and maintaining ecosystem health must be addressed concurrently (*197*). There has been a growing global trend toward incorporating sustainability into groundwater laws, regulations, and policies (*198*, *199*). Various management strategies, including forest and wetland conservation, desalination, wastewater recycling (*98*), managed aquifer recharge, water diversion projects, and green infrastructure development (*200*) are already being employed to bolster groundwater resilience, and will be critical to combat the growing problem of groundwater depletion globally.

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