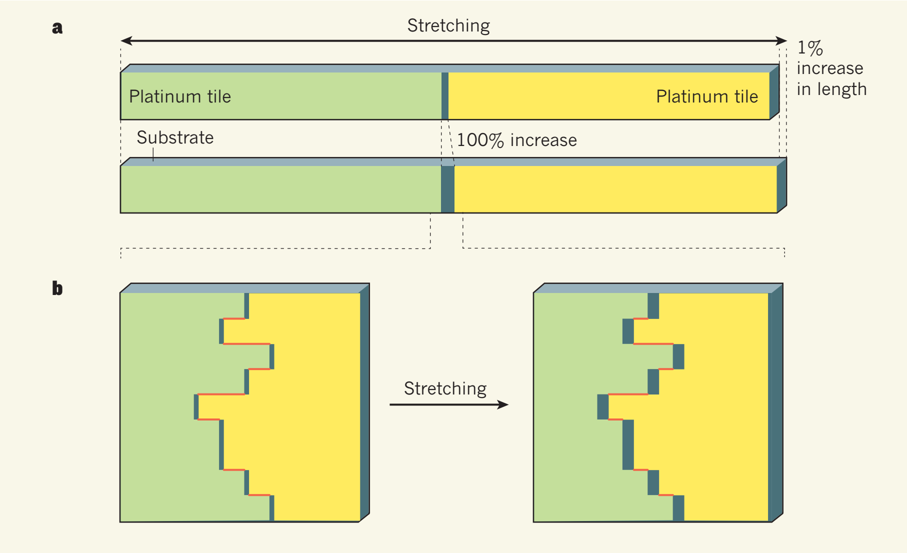

Figure 2 | Stretching rough cracks. Kang and colleagues' vibration sensor[3] is based on two effects on cracks in a platinum layer laid on a soft substrate: geometric amplification (**a**) and corrugation (**b**). When the device is stretched, the width of the crack that separates two platinum tiles increases by a much larger factor than the device as a whole, because the tiles are rigid. Shown here is a crack-width increase of 100% for a system stretched by 1%; this corresponds to an amplification factor of 100. Corrugation of the cracks at the nanoscale means that, on stretching, lateral contacts (red) between the tiles remain and allow electrical current to flow in the crack if a voltage is applied to the system. The electrical conductivity of the device is proportional to the total contact area between the tiles and thus depends on the amount of deformation.

the tiles themselves essentially undeformed.

Although tiling with extremely fine interstices (generated by controlled cracking of the platinum layer) introduces geometric amplification in Kang and colleagues' device, this feature by itself does not explain how deformation during a cycle of stretching and compression is actually transformed into an electrical signal proportional to the amount of deformation. Indeed, with the idealized system sketched in Figure 2a, electrical conductivity would immediately be lost when conducting (stiff) tiles start to separate upon stretching — that is, as soon as even the slightest deformation occurs.

In their study, Kang *et al.* take advantage of a particular property of cracks in platinum, their roughness at the nanoscale. Corrugations associated with such roughness provide lateral contacts (Fig. 2b) that enable electrical conductivity even when the gap between the platinum tiles increases. Hence, the ultrasensitivity of the sensor to vibration is due to the combination of two properties of the cracks in the platinum layer: their width in the nanometre range, which leads to geometric amplification, and their roughness at the nanoscale, which provides an electrical signal that depends on the amplitude of the deformation.

Kang and colleagues demonstrate that their sensor can be incorporated into devices to record minute vibrations such as musical sounds or the flapping of a ladybird's wings. Despite these impressive practical applications, the analogy with the spider's lyriform sensor is not complete. The only feature translated into the authors' system is geometric amplification. The biological sensing mechanism is entirely different (it is based on the firing of neurons rather than the measurement of electrical resistivity) and many other aspects of the spider's organ, such as its tunable sensitivity to different vibration-frequency ranges, are not reproduced. Although it may not be necessary to have these features included in a technical system, we are still far away from an artificial sensory system with a performance similar to that of the spider organ, whose evolution going back to the origins of the Chelicerata group of arthropods has been 1,000 times longer than the existence of humans. ■

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HYDROLOGY

When wells run dry

A global analysis reveals growing societal dependence on the use of non-renewable freshwater resources that depletes groundwater reserves and undermines human resilience to water scarcity in a warming world.

RICHARD TAYLOR

That freshwater reserves are in decline in many parts of the world is not only of great scientific interest, but of profound societal concern. Reports of groundwater depletion[1,2] and declining river and lake levels[3] provide compelling evidence of regional freshwater use exceeding its renewable supply. Quantifying freshwater supply and use around the world is, however, a substantial technical challenge. In one of the most comprehensive analyses so far, published in *Environmental Research Letters*, Wada and Bierkens[4] estimate the supply and use of fresh water from 1960 to 2099. They use both historical records and future projections that include substantial demographic and climate-related changes expected this century. Their analyses reveal a steady rise in the non-renewable use of fresh water in many parts of the world that should be of global concern.

Irrigation currently accounts for 70% of global freshwater withdrawals[4]. The green revolutions of the past half century which dramatically increased food production, most notably in the United States and Asia, were driven primarily by the expansion of cultivated land under irrigation. Because irrigation redistributes fresh water withdrawn from aquifers, rivers and lakes to the land, it changes regional water balances by increasing consumptive use of fresh water through evapotranspiration.

Intensive irrigation can deplete freshwater sources. For rivers and lakes that are being replenished through present-day precipitation, the magnitude of their depletion is constrained by their limited total volume[5] (about 93,000 cubic kilometres worldwide) and the very visible impacts of overuse. By contrast, groundwater resources derived from precipitation over years to decades and, in some cases, millennia, enable substantial non-renewable use on account of their vast, distributed

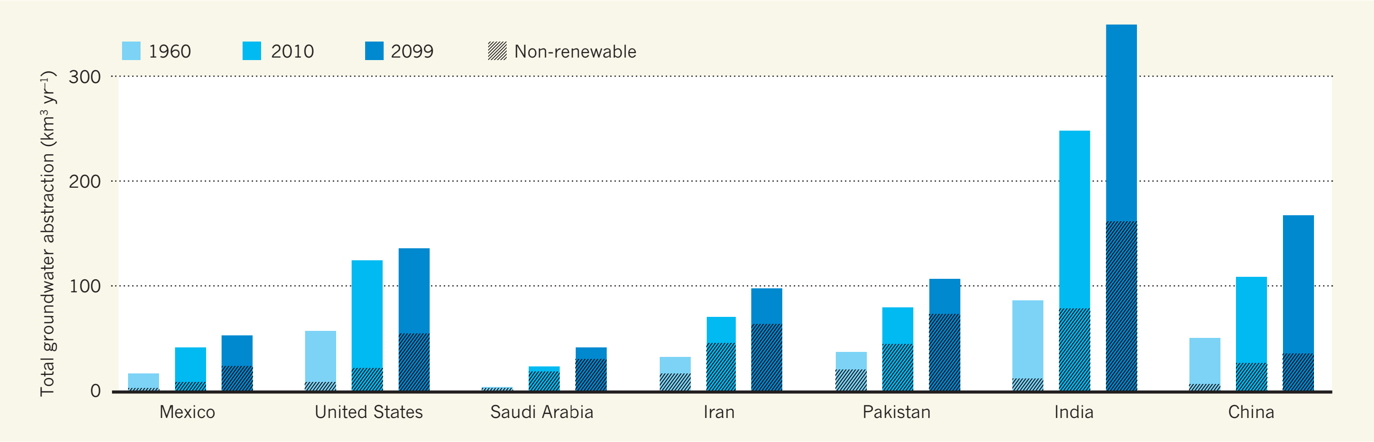

Figure 1 | Historical and projected groundwater withdrawals in the world's major irrigating countries. The chart shows total and non-renewable groundwater abstraction in India, the United States, China, Pakistan, Iran, Mexico and Saudi Arabia, as estimated by Wada and Bierkens[4], for 1960, 2010 and 2099; these countries accounted for 74% of global groundwater withdrawals in 2010. From 1960 to 2010, the estimated proportion of non-renewable groundwater withdrawals increases for all of these countries except Pakistan, where it remains stable but high at 58%.

volume[5] (about 10,500,000 km^3) and the fact that the impacts of overuse are largely invisible. Wada and Bierkens's study marks a significant advance on previous studies because it explicitly incorporates non-renewable uses of groundwater and surface water.

From a wide range of sources, the authors compiled the most detailed estimates yet of changing agricultural, industrial and household use of fresh water from around the world. Notably, these estimates account for return flows from irrigation as well as the recycling of water from industrial and domestic withdrawals. They then compared human freshwater use to estimates of freshwater supply derived from a global hydrological model and contributions from desalinization in coastal regions. The researchers also considered future projections of freshwater supply that explicitly factor in impacts of climate change, as represented by projections from five climate models using the 'middle of the road' scenario of global warming of 4 °C by the end of this century. They then overlaid distributed freshwater supply and use to define the proportion of consumptive use that derives from non-renewable groundwater abstraction and surface-water overabstraction. Here, non-renewable groundwater abstraction is groundwater use in excess of replenishment by recharge, whereas surface-water overabstraction is defined as the quantity of environmental flows denied to aquatic ecosystems though consumptive use.

Wada and Bierkens's study reveals that non-renewable freshwater use globally rose by 50% from 1960 to 2010 primarily as a result of the expansion of irrigation in the United States, China, India, Pakistan, Mexico, Saudi Arabia and northern Iran. Crucially, this rise is primarily attributed to non-renewable groundwater withdrawals (Fig. 1). As a result, groundwater is now estimated to account for 50% of freshwater withdrawals globally. Future projections indicate that climate change will exacerbate non-renewable freshwater use in the Mediterranean, southern Africa, the United States, Mexico and the Middle East. Globally, non-renewable freshwater use is projected to increase by one third by the end of the twenty-first century and to comprise 40% of human water consumption. This additional increase is expected to come largely from non-renewable groundwater withdrawals.

There are, however, some important limitations to this analysis. First, renewable freshwater resources in the tropics, and especially Africa, are not well represented by the global hydrological model. Simulated river discharge in some basins is two to three times greater than that observed[6] and is likely to reflect the model's systematic underestimation of tropical evapotranspiration. Second, the estimation of groundwater withdrawals does not consider how declining groundwater levels that result from the increasing non-renewability of these withdrawals raise the energy cost of bringing groundwater to the surface and allow access only to those able to afford deeper wells. Third, the production of a single future projection of freshwater supply and use based on mean output from five different climate models masks uncertainty in climate-change impacts. Fourth, the analysis does not consider water quality and how fresh water recycled from agricultural, industrial and domestic withdrawals may reduce rather than enhance freshwater supply. These limitations do not, however, undermine the robustness of the authors' central conclusion of the growing dependence of humans on the use of non-renewable freshwater resources.

Our increased use of such resources depletes groundwater storage and compromises the operation of aquatic ecosystems that sustain fisheries and other vital services. Indeed, groundwater depletion observed in some of the world's major agricultural regions[1] now threatens global food production. This depletion undermines our resilience not only to future increases in freshwater demand[4] but also to global warming. In a warming world, precipitation is intensified, occurring in fewer but heavier rainfall events[7]. The resulting impact of longer droughts and greater variability in river discharges will amplify human reliance on stored groundwater when this resource is in decline in many regions, and on surface-water storage when most of the world's major river systems are already dammed[8].

We need to better understand available groundwater storage and recharge responses to the intensification of rainfall, which is expected to be especially strong in the tropics[7]. Indeed, it is here where increases in freshwater use are projected to be most intense[4]. We also need to reduce human dependence on non-renewable fresh water through more efficient water use, particularly in irrigation, and by trading in 'virtual water'[9], which reduces local freshwater use through the import of food and other products. If we continue along our present trajectory, "when the well runs dry we (shall) know the worth of water"[10]. ■

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