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The use and re-use of unsustainable groundwater for irrigation: A global budget

Danielle S. Grogan
University of New Hampshire, Durham, danielle.grogan@unh.edu

Dominik Wisser
Zentrum für Entwicklungsforschung

Alexander A. Prusevich
University of New Hampshire, Durham, alex.proussevitch@unh.edu

Richard B. Lammers
University of New Hampshire, Durham, richard.lammers@unh.edu

Stephen E. Frolking
University of New Hampshire, Durham, steve.frolking@unh.edu

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LETTER

The use and re-use of unsustainable groundwater for irrigation: a global budget

Danielle S Grogan[1,3], Dominik Wisser[1,2], Alex Prusevich[1], Richard B Lammers[1] and Steve Frolking[1]

[1] Institute for the Study of Earth, Oceans, and Space, University of New Hampshire, Durham, NH 03824, United States of America
[2] Center for Development Research (ZEF), Zentrum für Entwicklungsforschung, Walter-Flex-Straße 3, D-53113 Bonn, Germany
[3] Author to whom any correspondence should be addressed.

E-mail: danielle.grogan@unh.edu

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Abstract

Depletion of groundwater aquifers across the globe has become a significant concern, as groundwater is an important and often unsustainable source of irrigation water. Simultaneously, the field of water resource management has seen a lively debate over the concepts and metrics used to assess the downstream re-use of agricultural runoff, with most studies focusing on surface water balances. Here, we bring these two lines of research together, recognizing that depletion of aquifers leads to large amounts of groundwater entering surface water storages and flows by way of agricultural runoff. While it is clear that groundwater users will be impacted by reductions in groundwater availability, there is a major gap in our understanding of potential impacts downstream of groundwater pumping locations. We find that the volume of unsustainable groundwater that is re-used for irrigation following runoff from agricultural systems is nearly as large as the volume initially extracted from reservoirs for irrigation. Basins in which the volume of irrigation water re-used is equal to or greater than the volume of water initially used (which is possible due to multiple re-use of the same water) contain 33 million hectares of irrigated land and are home to 1.3 billion people. Some studies have called for increasing irrigation efficiency as a solution to water shortages. We find that with 100% irrigation efficiency, global demand for unsustainable groundwater is reduced by 52%, but not eliminated. In many basins, increased irrigation efficiency leads to significantly decreased river low flows; increasing irrigation efficiency to 70% globally decreases total surface water supplies by ∽600 $\mathrm{km}^3\ \mathrm{yr}^{-1}$. These findings illustrate that estimates of aquifer depletion alone underestimate the importance of unsustainable groundwater to sustaining surface water systems and irrigated agriculture.

1. Introduction

Groundwater is critical to global food production, supplying nearly half of all water used in irrigated agriculture [1, 2]; surface water (e.g. rivers and reservoirs) supplies the rest. Both satellite- and model-based estimates of global groundwater depletion show that aquifers in important agricultural regions—including parts of India, China, and the U.S., the world's largest food producing nations—are losing mass [1, 3–7], and cannot continue providing current levels of groundwater supplies indefinitely. Unsustainable groundwater provides as much as ∽20% of global irrigation water supplies [4, 6], and in both China and India this water is directly responsible for approximately one quarter of crop production [8, 9]. Groundwater pumping increases surface water storage volumes and river fluxes over several major agricultural aquifer regions, including the High Plains aquifer in North America, the North China Plain, and parts of north-west India [2]. These increases in surface water storage are due to inefficiencies in water extraction, transport, and use, all of which can lead to additional runoff.

Here, we use the definition of unsustainable groundwater (UGW) most commonly utilized by macro-scale hydrology modeling [5, 6, 10] and remote sensing [3] analyses: the average annual groundwater extracted in excess of average annual recharge. While

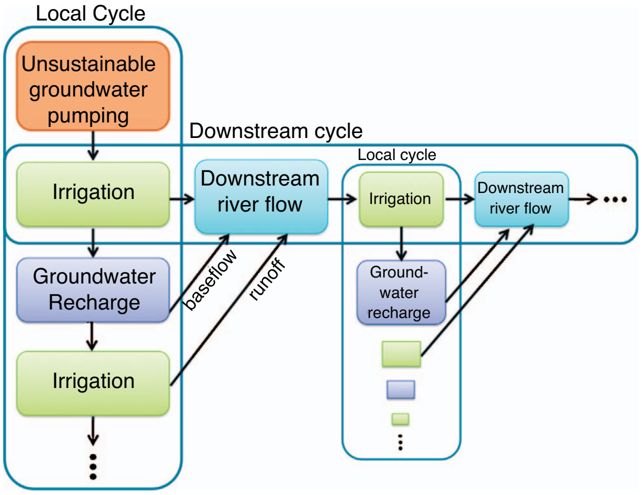

Figure 1. The unsustainable groundwater re-use cascade. Each time unsustainable groundwater (UGW) is extracted for irrigation, a portion of the extracted water becomes groundwater recharge and/or runoff due to irrigation inefficiencies. Any UGW that becomes groundwater recharge can be re-extracted locally, initiating a local cycle. UGW that becomes runoff (surface or sub-surface through groundwater recharge) enters the river system and travels downstream where it can be re-extracted, initiating a downstream cascade of local cycles.

this definition does not account for potentially complex surface water-groundwater interactions [1], it serves as a large-scale indicator of groundwater depletion [4–6, 10].

The efficiency of irrigation water use is typically quantified using the classical irrigation efficiency concept [11, 12]. Classical irrigation efficiency is defined as the ratio of beneficial crop water use to gross irrigation water extracted from water sources. This ratio is always <1 due to inevitable water losses to ‘non-beneficial’ (i.e. non-crop) evapotranspiration, conveyance losses (e.g. leaky canals), or on-field losses due to runoff and percolation. While classical irrigation efficiency may be sufficient for assessing field-scale water use efficiency, it is now recognized as insufficient at larger scales [13–15], leading multiple studies to highlight the need to understand return flows from irrigated areas [13–18], and the development of over a dozen different metrics to quantify irrigation water re-use at field- to basin-scales [13]. Alternative metrics to classical irrigation efficiency include the basin closure concept, which assesses water use efficiency at a whole-basin scale by comparing basin inflows to outflows [19], the water re-use index, which quantifies surface water re-use for irrigation, industrial, and domestic water use, along a river transect [14], and the net efficiency concept, which aims to assess what proportion of agricultural runoff is suitable for re-use [15]. See ref. 13 for a thorough review of the topic.

Despite an ongoing debate over the usefulness of classical versus alternative irrigation efficiency metrics [13, 20], groundwater has largely been left out of the discussion. Most alternative metrics either cannot separate unsustainable groundwater (UGW) from analyses of sustainable groundwater and surface water supplies, or explicitly assume that no UGW is used [e.g. 14]. Some alternative metrics include groundwater as an input to the basin system [13, 21], but do not separate sustainable from unsustainable sources. Classical irrigation efficiency is a misleading indicator of water use efficiency in basins that rely on UGW for irrigation [21, 22], because a fraction of the unused portion of extracted UGW can return to both surface water and groundwater pools. Estimates of global average classical irrigation efficiency range from 37% to 50% [11, 12], indicating that significant amounts of extracted groundwater become runoff and recharge. Runoff and recharge due to inefficient irrigation can then be re-extracted and used either within the local region (through groundwater recharge) or downstream (through rivers), leading to a ‘cascade’ of re-use cycles [13] (figure 1).

Groundwater extractions can alter surface water storage volumes and river flows [2, 23]; groundwater is also known to contribute to ecologically important river low flows [4, 24]. This implies that as aquifers are depleted, a reduction in groundwater pumping will impact surface water storage and flows. Groundwater pumping may also be reduced if efforts are made to increase classical irrigation efficiency [25, 26]; while net water savings may be achieved this way, it is important to assess the impact of such changes on river flows, especially in light of low flows required to sustain riverine ecosystem services [e.g. 24].

We introduce both the UGW irrigation re-use index $\boldsymbol{R}$, as well as the first estimate of the minimum amount of global unsustainable groundwater required to sustain the current agriculture system (i.e. UGW demand in a 100% irrigation efficiency scenario). We also quantify how UGW use and re-use contributes to ecologically important low flows in river systems. The unsustainable groundwater re-use index $\boldsymbol{R}$ quantifies how many times extracted UGW is re-used within a river basin due to irrigation inefficiencies. This index allows UGW re-use to be quantified independently from surface water re-use. The minimum unsustainable groundwater dependence is the quantity of UGW extraction required to meet irrigation water requirements under a classical 100% irrigation efficiency scenario. Such a scenario is hypothetical, but the metric is useful because it quantifies the lower bound of the current agriculture system's reliance on unsustainable water sources. Quantifying UGW contribution to river low-flows shows the current reliance of riverine ecosystems on the human activity of UGW pumping.

2. Methods

We calculate gross irrigation water requirements, UGW extraction, and the amount of UGW that enters river systems and groundwater recharge using the global gridded Water Balance Model (WBM) [10, 27] (further model details are in supplemental methods available at stacks.iop.org/ERL/12/034017/mmedia). WBM is a process-based, daily time step model that simulates vertical water exchange between the land surface and atmosphere, and horizontal water transport through runoff and stream networks; it includes representations of hydrologic infrastructure, land use/land cover types, and irrigation. The model simulates these water flows on a daily time step; results shown here are annual aggregates. See references [10] and [27] for full model documentation. UGW that enters streams by way of runoff and baseflow is tracked downstream through a river network, and can be extracted from the (well-mixed) rivers, large reservoirs, and groundwater recharge pools to meet irrigation water requirements. In all WBM simulations, UGW is extracted and applied only to irrigated cropland. Return flows from cropland are assumed to directly enter rivers and groundwater recharge. Use and re-use of UGW is tracked through model storages and flows, including soil moisture, evapotranspiration (but not subsequent precipitation), reservoir storage, groundwater storage, baseflow, and river discharge. All results reported here are 30-year mean annual values, and one standard deviation of interannual variability of this climatology is given based on contemporary distribution of irrigated crops and weather variability from 4 different climate input datasets (model details in supplemental materials and methods). Land use, including irrigated areas, remain constant through all simulations, as these simulations are meant to represent the current agricultural system.

2.1. Irrigation

Crop maps of both irrigated and rainfed land, along with crop type and season length are from the MIRCA2000 database [28]. National statistics on the ratio of surface water (from rivers and reservoirs) to groundwater (groundwater recharge and UGW) supplies used for irrigation at a country level [11] are used to determine source of irrigation water withdrawals in the Water Balance Model (WBM). WBM's grid-cell level irrigation water extractions occur in three stages: (1) surface water and renewable groundwater (i.e. groundwater recharge) are extracted in the FAOSTAT-based ratio of surface- to groundwater [11] if possible; (2) if (1) does not fully meet all demand, then remaining irrigation water demand is fulfilled using any remaining surface water or renewable groundwater, if possible; and (3) if irrigation water demand is still not met after (2), then UGW is extracted to fulfill the remaining demand. All other methods for irrigation water demand and application are based on reference [34], as described in reference [10] and appendix A of reference [27]. See supplemental methods for validation of UGW extractions and total groundwater extractions.

The inefficient portion of all irrigation water extractions (the difference between gross and net irrigation water volumes) is split into three portions. First, it can evaporate to meet local evaporative demand:

$$E = (\mathrm{PET}_i - \mathrm{AET}_i) \times \mathrm{IrrAreaFrac}_i \tag{1}$$

where PET_i is the potential evapotranspiration volume for grid cell i, AET_i is the actual evapotranspiration for entire grid cell i (calculated after applying irrigation water to soils within the irrigated area), and $\mathrm{IrrAreaFrac}_i$ is the fraction of grid cell i that is irrigated. After evaporation occurs, the remaining inefficient portion of irrigation water extractions is divided equally between surface runoff and groundwater recharge. Changing this distribution of return flows has little impact (1%–8%) in total UGW re-use, although it alters the relative proportion of UGW_r through surface water versus groundwater. See supplemental methods for a sensitivity analysis of this parameterization of return flows.

2.2. Tracking UGW

WBM tracks UGW, as well as non-UGW water sources (precipitation and snowmelt) of water through all model stocks and flows. At each daily time step, the proportion of each stock is updated based on inflows and outflows of water, and that water's proportional composition of water sources. We assume all stocks are well mixed. In this way, a unit of water retains its identity as UGW even as it passes through surface water flows (the atmospheric portion of the hydrologic cycle is not modeled). We define UGW extracted directly from groundwater as UGW_i, and UGW extracted from surface water flows and groundwater recharge pools as UGW_r.

2.3. Unsustainable groundwater re-use metric, *R*

Basins that re-use UGW are more dependent upon this unsustainable source of water than estimates of aquifer depletion alone imply. We define a dimensionless UGW re-use factor, ***R***, as:

$$\boldsymbol{R} = \mathrm{UGW}_r/\mathrm{UGW}_i \tag{2}$$

2.4. Assessing ecological low-flows

Freshwater ecosystems depend upon a range of river characteristics, including low-flows, high-flows, and water quality [24]. Groundwater is known to support ecologically important low-flows [4]; here, we assess the role of UGW in maintaining these low flows. Following refs. 4 and 24, we use Q90 as a measure of ecologically important low-flows, where Q90 is the monthly mean river discharge exceeded 90% of the time over a 30 year model simulation period. To quantify how increasing irrigation efficiency and reductions in UGW availability will alter low flows, we developed three model simulations, referred to here as Baseline (*Base*), 70% Global Irrigation Efficiency (*GIE70*), and No UGW (*NoUGW*). The *Base* simulation tracks UGW under current (c. year 2000) conditions, as described above. In *GIE70*, irrigation efficiency is increased to 70% (current global maximum irrigation efficiency [11]) in all model grid cells with irrigation. In *NoUGW*, irrigation efficiency remains at current levels, but no UGW_i is extracted, and total irrigation demand is not met if gross demand is greater than sustainable water supplies. The *GIE70* simulation represents a scenario in which high irrigation efficiency is achieved globally, and the *NoUGW* simulation represents a scenario in which aquifer depletion or policy prohibits UGW pumping.

2.5. A lower bound on unsustainable groundwater dependence

River systems are a network of connected runoff, discharge, water extractions, and return flows. Therefore, a systems-analysis approach is required to assess how increasing irrigation efficiency will alter the balance of total irrigation water demand, and supply from sustainable versus unsustainable sources. To quantify the effect of increasing irrigation efficiencies, we simulated a series of incremental increases in the national minimum irrigation efficiency: 34% (current minimum national irrigation efficiency; *11*), 40%, 50%, . . . , 100%. With each increase, the irrigation efficiencies of all model grid cells that are below the new minimum threshold were raised to that threshold. These simulations represent hypothetical changes; we do not propose pathways or timelines for implementing these changes, but rather use these simulations to quantify the potential lower bound for global UGW_i demand. At 100% efficiency, UGW_r goes to zero, and gross irrigation water demand is equal to net irrigation water demand. The 100% irrigation efficiency scenario identifies the minimum global UGW_i dependence, i.e. the minimum potential volume of UGW_i that is required to meet current irrigation water requirements.

2.6. Model uncertainty and validation

We assess the primary sources of uncertainty in this analysis, which are: 1) climate input data sets, 2) rice paddy percolation rates, 3) irrigation return flow distribution between surface runoff and groundwater recharge, and 4) within-basin hydro-infrastructure uncertainty. See supplemental materials and methods S1 for details of the uncertainty analysis. We find the first three sources of uncertainty are small, altering simulated UGW demands in the *Base* scenario by <10% each. Uncertainty due to within-basin hydro-infrastructure (e.g. canals), however, is larger. Altering the modeled representation of canal infrastructure results in simulated UGW demands of 232 (±23) km^3 yr^{-1} to 663 (±55) km^3 yr^{-1} in the *Base* simulation. This range closely matches the range of uncertainty in aquifer depletion estimated by [6].

Simulated irrigation water demands—total, from surface water, and from groundwater—are compared to FAO-reported country-level statistics on irrigation water use. Considering countries for which there are comparable values for each category, the Pearson Correlation Coefficient (R^2) of WBM-simulations compared to FAO data is 0.93 for irrigation water withdrawals, 0.91 for groundwater withdrawals, and 0.75 for surface water withdrawals. We also find that WBM simulates global and basin-level UGW volumes that are generally similar to previous model studies [4], though with notable discrepancies for some basins. See supplemental materials and methods S2 for further model validation details.

3. Results

3.1. A global budget of unsustainable groundwater

We use the following definitions:

- UGW_i = initial UGW withdrawals from aquifers
- UGW_r = UGW that is re-used by extraction from rivers, reservoirs, and groundwater recharge.

We find that global UGW_i withdrawn for irrigation is 378 (±49) km^3 yr^{-1}, or ∽12% of gross irrigation (3 244 (±240) km^3 yr^{-1}). By tracking re-use of this water through rivers and groundwater recharge, we find that UGW_r is 357 (±62) km^3 yr^{-1}, which is 7%–15% of gross irrigation. The Water Balance Model tracked UGW_i through the surface components of the hydrologic cycle, and identified the portion that enters the atmosphere as crop ET and non-beneficial evaporation, and discharges to the ocean and to internal (endorheic) basins (figure 2). Note that the total re-use volume (UGW_r, 357 (±62) km^3 yr^{-1}) represents both the efficient and inefficient water volumes, so a significant portion of these extractions return to rivers and groundwater recharge pools numerous times (figure 1) through the simulation (i.e. both local cycles and downstream cycles of re-use occur) (figure 2, circular arrows).

Accounting for both UGW_i and UGW_r, we find that overall UGW (UGW_i and UGW_r) contributes 238

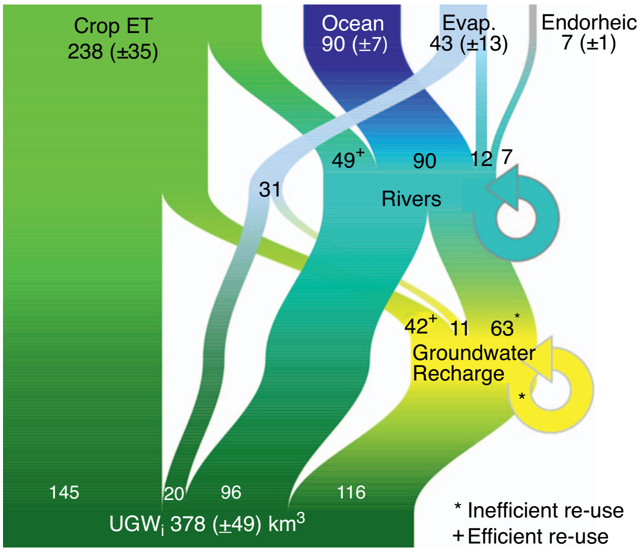

Figure 2. A global budget of unsustainable groundwater (UGW). This diagram shows the global volume of UGW that is pumped initially (UGW_i), and its trajectory through the stocks and flows of the hydrological cycle's surface components. The direct movement of UGW_i to crop ET shows the efficient portion of UGW_i irrigation extractions (38%). The inefficient portion is split between non-beneficial evaporation (20 km^3 yr^{-1}), runoff to rivers (96 km^3 yr^{-1}), and groundwater recharge (116 km^3 yr^{-1}). Both the river and groundwater recharge pools have further water extractions for irrigation; the diagram shows only the volume of UGW_r extracted from these pools, excluding any sustainable water use. These extractions are also split into efficient (directly to crop ET) portions, and inefficient portions. The inefficient portions are further divided, becoming non-beneficial evaporation (12 km^3 yr^{-1} from rivers, 11 km^3 yr^{-1} from groundwater recharge), and returning to the river and groundwater recharge pools (circular arrows). Numbers marked with an asterisk (*) are return flows from the inefficient portion of UGW_r irrigation water use; numbers marked with a plus ($^+$) are the efficient re-use of UGW_r irrigation extracted from river and groundwater recharge pools. The total amount of UGW_i and UGW_r contribution to crop evapotranspiration is 238 (±35) km^3 yr^{-1}, or 63% of UGW_i; 145 (±18) km^3 yr^{-1} is from the efficient portion of extracted UGW_i; the remainder is from the efficient portion of UGW_r re-used through rivers and groundwater recharge.

(±35) km^3 yr^{-1} to crop evapotranspiration (ET) (figure 2). This crop ET volume is due to 145 (±18) km^3 yr^{-1} of direct use of the efficient portion of UGW_i, and an additional 42 (±9) km^3 yr^{-1} of crop ET from the efficient portion of UGW_r through groundwater recharge and 49 (±11) km^3 yr^{-1} of crop ET from the efficient portion of UGW_r through rivers. In total, 63% (±9%) of UGW_i extracted from aquifers becomes crop ET. Only 97 (±8) km^3 yr^{-1}, or 26% (±2%), of the volume extracted from aquifers leaves river systems as discharge to the ocean and internal (endorheic) basins (figure 2). UGW discharge directly to the ocean (not including internal basins) is 90 (±7) km^3 yr^{-1}, or 0.25 (±0.02) mm Sea-Level Equivalent, which is within the range of previous estimates (0.02–0.8 mm) [7, 29]. An additional 43 (±13) km^3 yr^{-1} is lost to non-beneficial evaporation from fields and conveyance structures.

3.2. Unsustainable groundwater re-use

As defined in equation (2), $\boldsymbol{R}$ is a measure of the degree of UGW re-use in a river basin. For $\boldsymbol{R} > 1$, the volume of UGW re-used in a basin exceeds the original volume of water withdrawn: $UGW_r > UGW_i$. If $\boldsymbol{R} > 1$, $UGW_i + UGW_r$ effectively acts as twice as much water (or more) than the initial extraction volume indicates within the basin irrigation system; this is made possible by the local and downstream cascades of re-use (figure 1).

The largest UGW_i extractions and $\boldsymbol{R}$ values both occur in South and East Asia (figure 3). By overlapping maps of irrigated areas [28] and population density data [30] with the basin re-use factor map, we quantify the irrigated area and population for all $\boldsymbol{R} > 0$ values (figure 4). Basins with $\boldsymbol{R} > 1.0$ contain 33 million hectares of irrigated land (11% of total) and are home to 1.3 billion people (17% of total).

3.3. Unsustainable groundwater supports ecological low-flows

Comparison of river low-flow levels in model simulations *Base*, *GIE70* and *NoUGW* show that ecological low-flows can be highly dependent upon unsustainable groundwater pumping. In the *GIE70* simulation, Q90 decreases in nearly all sub-basins (figure 5(*a*)). This result highlights the paradox of irrigation efficiency: an inefficient system requires more water extractions from all irrigation water sources, yet it also returns more water to the renewable sources. In sub-basins with decreased Q90, the increased efficiency reduced the amount of UGW_i, and therefore also reduced return flows to the river system. Increasing irrigation efficiency to 70% causes particularly severe decreases in Q90 in the Indus (India and Pakistan) and the Ganges (India) basins. The impact on low flows is even stronger in the *NoUGW* simulation (figure 5(*b*)), and is expanded to parts of the western, southwestern, and central U.S, the Middle East, Central Asia, northeastern China, Eurasia, and Australia (figure 5(*b*)). Q90 in some sub-basins decreases to 0 m^3 s^{-1} (complete drying of the river through the sub-basin), indicating that the ecologically

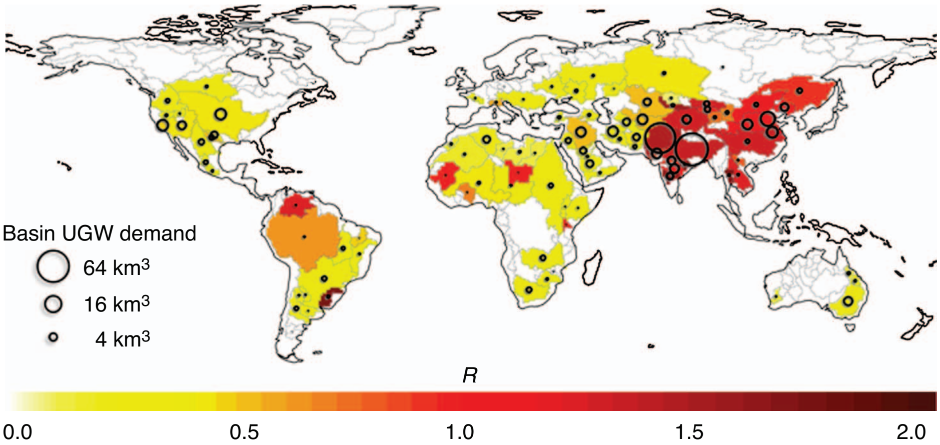

Figure 3. Unsustainable groundwater pumped and re-used. Basins are colored according to their UGW re-use factor, ***R***; circles show each basin's UGW$_i$ [km^3 yr^{-1}], with circle size proportional to the square root of UGW$_i$. Basins with both high ***R*** (red) and large UGW$_i$ (circles) are not only highly dependent upon UGW$_i$, but they are also dependent upon re-use of UGW$_r$, and have a low potential to reduce this dependency through increased irrigation efficiency. ***R*** > 1.0 indicates that UGW re-use in a river basin is greater than the original volume withdrawn. Each basin's ***R*** value is the mean value of all 0.5° grid cells within the basin; only basins with areas >100 000 km^2 and ***R*** > 0.1 are colored.

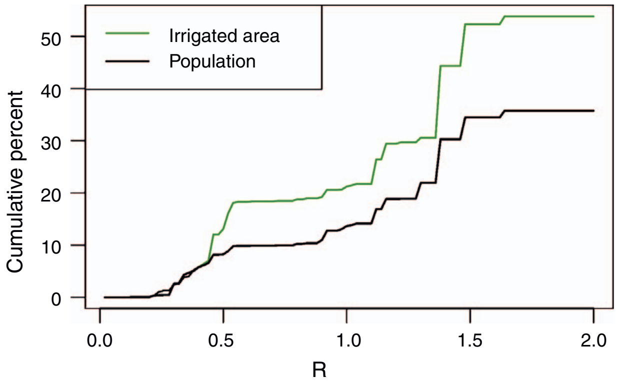

Figure 4. Cumulative irrigated area and population with increasing index *R*. Cumulative irrigated area and population with increasing *R* are generated from overlapping maps of irrigated areas, population density and river basin UGW$_r$. The cumulative irrigated area percentage does not reach 100% because regions with UGW$_i$ demand <1 km^3 yr^{-1} are not included; cumulative population does not reach 100% because of large populations in regions with no irrigation.

important Q90 flow is entirely reliant upon UGW pumping and re-use. For example, Q90 across the lower 1200 km of the Indus basin decreases by up to 60% in the *GIE70* simulation, and up to 100% in the *NoUGW* simulation (figure 6(*a*)). While Q90 is important to assess for ecological management, it is also notable that the entire flow regime of the Indus River is changed by increased irrigation efficiency and reduced UGW pumping (figure 6(*b*)).

3.4. Global effects of increasing irrigation efficiency

Much of the debate over water re-use metrics, measurements, and concepts stems from proposals to increase irrigation efficiency [6, 13, 25]. Several studies have shown that irrigation efficiency improvements can lead to unintended increased water use due to the perceived increase in water availability [31, 32]—known as Jevons' Paradox [33]—but none have assessed the downstream impact of reducing upstream groundwater pumping. The *GIE70* simulation decreases total global surface water supplies by ∽600 km^3 yr^{-1}; however, it also decreases the gross irrigation water demand by 1 450 km^3 yr^{-1} (a 45% reduction from *Base*), and decreases aquifer depletion from UGW pumping by 124 km^3 yr^{-1} (33% reduction from *Base*). While the decrease in total surface water supplies and ecologically important low-flows may be of concern, the benefits of reducing irrigation water demand and alleviating aquifer depletion must also be considered.

By modeling incremental increases in minimum irrigation efficiency (see section 2.5 above), we find that the mimimum global UGW$_i$ dependence is 180 (±28) km^3 yr^{-1} (figure 7), a reduction of ∽52% from current UGW$_i$ demand. To reduce UGW$_i$ demand further will require additional or alternative changes to irrigated agriculture (e.g. switching to less water consuming crops, or varieties with increased water use efficiency [6]). For each increased irrigation efficiency scenario, we also quantified the total amount of UGW

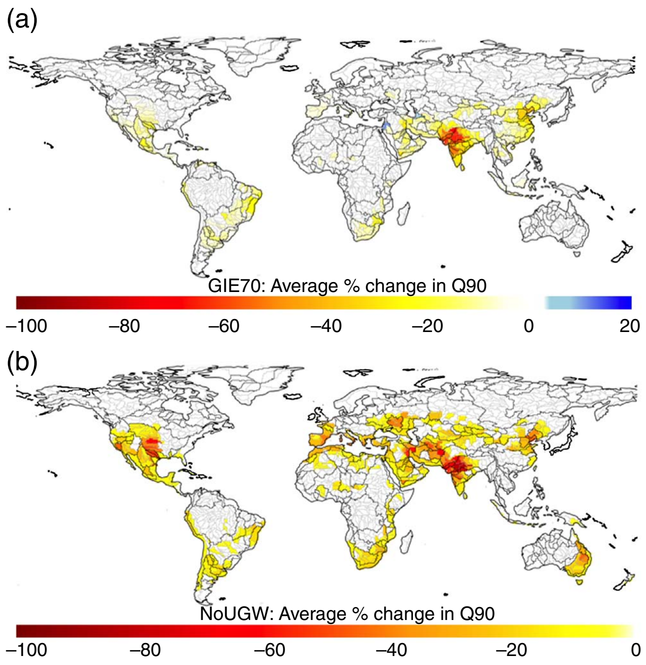

Figure 5. Percent change in sub-basin low-flows in *GIE70* and *NoUGW* simulations. Q90 is the average monthly river discharge exceeded 90% of the time, based on 30 years of model simulations and averaged over 4 climate input datasets. The average % change in Q90 is the difference between monthly mean Q90 in the *Base* simulation and the experimental simulation. Sub-basin values are aggregated from all grid cells within the sub-basin; changes of −5% to 5% are not shown (white); sub-basins are shown (instead of whole basins) because large basins have significant spatial variability. (*a*) Average % change in monthly Q90 between the *Base* simulation and the *GIE70* simulation, in which all grid cells increase their irrigation efficiency to 70%. Red (blue) indicates that Q90 decreases (increases) with increased irrigation efficiency. (*b*) Average % change in monthly Q90 between the *Base* simulation and the *NoUGW* simulation in which all grid cells have the same irrigation efficiency as in the *Base* simulation, but do not have access to UGW. There are no positive changes in the NoUGW simulation.

used for agriculture ($UGW_i + UGW_r$), which is equivalent to the water deficit that would occur under each irrigation efficiency scenario if UGW resources were unavailable (figure 7). At current efficiency levels, total UGW ($UGW_i + UGW_r$) is 748 (±107) $km^3\ yr^{-1}$, approximately one quarter of global gross irrigation water requirements. This shows that, with no increase in irrigation efficiency, the loss of UGW resources—either due to complete depletion of aquifers, or for economic or regulatory reasons—would lead to a 25% shortage of irrigation water supplies globally. Under a 100% efficiency scenario, UGW_i makes up about 15% of global gross irrigation water requirements, indicating that a loss of UGW resources under such a high efficiency scenario would lead to a 15% shortage of irrigation water supplies globally.

4. Discussion and conclusions

Use of unsustainable groundwater for irrigation has been the focus of several recent global-scale analyses [1, 4, 6], all showing aquifer depletion and the spatial patterns of regional reliance on groundwater for irrigated agriculture. However, there are significant differences in how this water is used and re-used once it has been extracted. Here, we find that the unsustainable groundwater irrigation re-use index, ***R***, can be used in conjunction with estimates of unsustainable groundwater extraction to reveal the reliance of irrigated agriculture not only on unsustainable groundwater, but also on re-use of this water. Basins with high re-use factors have an outsized reliance on this unsustainable resource, which estimates of aquifer depletion alone do not accurately assess. Additionally, basins with high re-use factors have a diminished ability to reduce their reliance on unsustainable groundwater by improving irrigation efficiency, as greater efficiencies lead to decreased re-use. By finding the potential minimum amount of unsustainable groundwater required by irrigated agriculture, we are able to quantify the volume by which other (non irrigation efficiency) water saving measures must reduce the reliance on UGW in order to achieve sustainable groundwater use.

We show here that there is a direct connection between the human activity of extracting groundwater in excess of recharge, and ecologically important river low-flows. Without unsustainable groundwater entering surface water systems, low-flows will decrease across many agricultural regions. In some sub-basins, monthly low-flows are decreased to 0 $m^3\ s^{-1}$ under a sustainable groundwater use scenario, indicating that riverine ecosystems are dependent upon human extraction of an unsustainable resource. There have been several calls for increasing irrigation efficiency [25, 26] as a means of reducing agricultural water demand from all sources (sustainable and

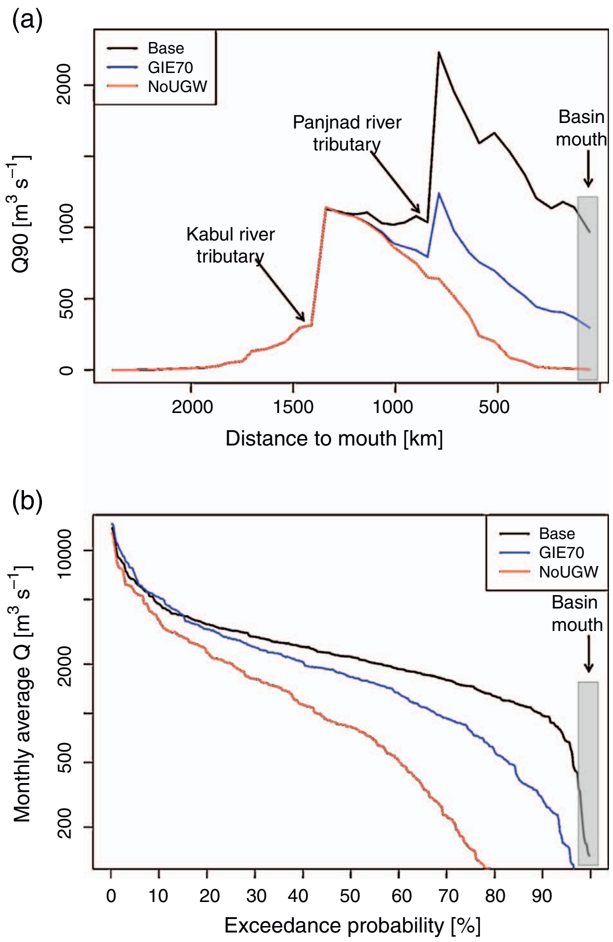

Figure 6. Change in Q90 and flow exceedance probability in the Indus River basin under *Base, GIE70*, and *NoUGW* simulations. (*a*) Q90 under *Base, GIE70*, and *NoUGW* simulations along a transect of the Indus river basin. The transect follows the main stem of the Indus: at tributary intersections, it follows the tributary with the largest upstream area. Major tributary junctions are labeled; the basin mouth is shown in the gray box. (*b*) The flow exceedance probability at the Indus basin mouth shows that not only does the Q90 value change at the river mouth, but also the entire hydrologic regime is shifted under *GIE70* and *NoUGW* simulations. Note the log scale on the *y*-axis in panel (*b*).

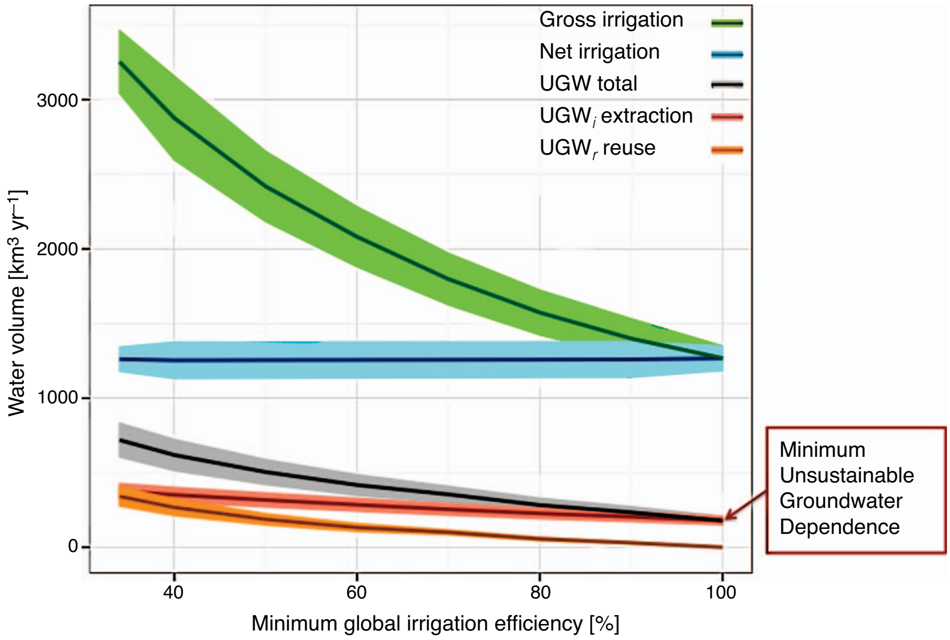

Figure 7. The effect of increasing irrigation efficiency. Changes in global gross irrigation water requirements (green line), UGW$_i$ (red line), UGW$_r$ (orange), total UGW (black) as the minimum global irrigation efficiency increases. At 100% irrigation efficiency, 180 (±24) km^3 yr^{-1} UGW is still required to meet contemporary irrigation water requirements. Shaded bands show 1 standard deviation due to 30 years of inter-annual climate variability across 4 climate input datasets.

unsustainable). We find that increasing efficiency can reduce the demand for unsustainable groundwater pumping by as much as 52%, which is a significant and positive outcome. However, such a drastic change has unintended consequences: it will also substantially reduce major river low-flows in many basins. By looking at the entire flow exceedance probability profile of the Indus River, we show that not only are low-flows affected by irrigation efficiency changes, but also the entire hydrologic regime is altered. Such shifts in hydrologic regime must be considered by water managers when planning for future increases in irrigation efficiency and maintaining flows for ecological use, human extractions, and hydro-infrastructure such as hydropower. These results highlight the need for careful consideration of both the potential benefits (e.g. reduced water demand) and negative impacts (e.g. reduced ecological low-flows) of changing irrigation efficiencies when searching for solutions to water stress challenges.

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References

[1] Aeschbach-Hertig W and Gleeson T 2012 Regional strategies for the accelerating global problem of groundwater depletion *Nat. Geosci.* **5** 853–61

[2] Doll P, Hoffmann-Dobrev H, Portmann F T, Siebert S, Eicker A, Rodell M, Strassbert G and Scanlon B R 2012 Impact of water withdrawals from groundwater and surface water on continental water storage variations *J. Geodyn.* **59–60** 143–56

[3] Rodell M, Velicogna I and Famiglietti J S 2009 Satellite-based estimates of groundwater depletion in India *Nature* **460** 999–1002

[4] Gleeson T, Wada Y, Bierkens M F P and van Beek L P H 2012 Water balance of global aquifers revealed by groundwater footprint *Nature* **488** 197–200

[5] Wada Y, van Beek L P H, van Kempen C M, Reckman J W T M, Vasak S and Bierkens M F P 2010 Global depletion of groundwater resources *Geophys. Res. Lett.* **37** L20402

[6] Wada Y, van Beek L P H and Bierkens M F P 2012 Nonsustainable groundwater sustaining irrigation: a global assessment *Water Resour. Res.* **48** W00L06

[7] Konikow L F 2011 Contribution of global groundwater depletion since 1900 to sea-level rise *Geophys. Res. Lett.* **38** L17401

[8] Grogan D S, Zhang F, Prusevich A, Lammers R B, Wisser D, Glidden S, Li C and Frolking S 2015 Quantifying the link between crop production and mined groundwater irrigation in China *Sci. Total Environ.* **511** 161–75

[9] Zaveri E, Grogan D S, Fisher-Vanden K, Frolking S, Lammers R B, Wrenn D H, Prusevich A and Nichols R E 2016 Invisible water, visible impact: groundwater use in Indian agriculture under climate change *Environ. Res. Lett.* **11** 084005

[10] Wisser D, Fekete B M, Vörösmarty C J and Schumann A H 2010 Reconstructing 20th century global hydrography: a contribution to the Global Terrestrial Network- Hydrology (GTN-H) *Hydrol. Earth Syst. Sci.* **14** 1–24

[11] Food and Agriculture Organization of the United Nations 2015 *Nations Food and Agriculture Organization of the United Nations Statistical Database (FAOSTAT)* (Rome: FAO)

[12] Postel S 1993 *Water in Crisis: A Guide to the World's Fresh Water Resources* ed P H Gleick (Oxford: Oxford Univ. Press)

[13] Simons G W H, Bastiaanssen W G M and Immerzeel W W 2015 Water reuse in river basins with multiple users: a literature review *J. Hydrol.* **522** 558–71

[14] Vorosmarty C J, Douglas E M, Green P A and Refenga C 2005 Geospatial indicators for emerging water stress: an application to Africa *Ambio* **34** 230–6

[15] Seckler D, Molden D and Sakthivadivel R 2003 The concept of efficiency in water resources management and policy *Water Productivity in Agriculture: Limits and Opportunities for Improvement* ed J W Kijne, R Barker and D Molden (Wallingford, UK/Columbo, Sri Lanka: CABI Publishing and International Water Management Institute)

[16] Keller A and Keller J 1995 Effective efficiency: a water use concept for allocating freshwater resources water resources and irrigation division *Discussion paper 22* Winrock International, Arlington, Virginia

[17] Gleick P H, Christian-Smith J and Colley H 2011 Water-use efficiency and productivity: Rethinking the basin approach *Water Int.* **36** 784–98

[18] Tornqvist R and Jarsjo J 2011 Water savings through improved irrigation techniques: basin-scale quantification in semi-arid environments *Water Resour. Manage.* **26** 949–62

[19] Molden D and Bos M G 2005 Improving basin water use in linked agricultural ecological and urban systems: seeing new flow paths and avoiding dead ends *Water Sci. Technol.* **51** 147–54

[20] Lankford B 2012 Fictions, fractions, factorials and fractures; on the framing of irrigation efficiency *Agric. Water Manage.* **108** 27–38

[21] Hafeez M M, Bauman B A M, Van de Giesen V and Vlek P 2007 Scale effects on water use and water productivity in a rice-based irrigation system (UPRIIS) in the Philippines *Agric. Water Manage.* **92** 81–9

[22] Foster S D and Perry C J 2010 Improving groundwater resource accounting in irrigated areas: a prerequisite for promoting sustainable use *Hydrol. J.* **18** 291–4

[23] de Graaf I E M, van Beek L P H, Wada Y and Bierkens M F P 2014 Dynamic attribution of global water demand to surface water and groundwater resources: Effects of abstractions and return flows on river discharges *Adv. Water Resour.* **64** 21–33

[24] Smakhtin V U, Revenga C and Doll P 2004 A pilot global assessment of environmental water requirements and scarcity *Water. Int.* **29** 307–217

[25] Gleick P 2001 Making every drop count *Sci. Am.* **284** 40–5

[26] Wada Y, Gleeson T and Esnault L 2014 Wedge approach to water stress *Nat. Geosci.* **7** 615–7

[27] Grogan D S 2016 Global and regional assessments of unsustainable groundwater use in irrigated agriculture *Doctoral Dissertations* 2 (http://scholars.unh.edu/dissertation/2)

[28] Portmann F, Siebert S and Doll P 2010 MIRCA2000—Global monthly irrigated and rainfed crop areas around the year 2000: a new high-resolution data set for agricultural and hydrological modeling *Glob. Biogeochem. Cycles* **24** GB1011

[29] Wada Y, Min-Hui L, Yeh P J-F, Reager J T, Famiglietti J S, Wu R-J and Tseng Y-H 2016 Fate of water pumped from underground and contributions to sea-level rise *Nat. Clim. Change* **6** 777–80

[30] United Nations, Department of Economic and Social Affairs, Population Division 2013 *World Population Prospects: The 2012 Revision* (United Nations, New York)

[31] Contor B A and Taylor R G 2013 Why improving irrigation efficiency increases total volume of consumptive use *Irrig. Drain.* **62** 273–80

[32] Ward F A and Pulido-Velazquez M 2008 Water conservation in irrigation can increase water use *Proc. Natl Acad. Sci. USA* **105** 18215–20

[33] Alcot B 2005 Jevons' paradox *Environ. Econ.* **54** 9–21