Supplementary information for

Global Economic Limits of Groundwater When Used as a Last Resort for Irrigation

Marc F.P. Bierkens, Inge E.M. de Graaf, Stephanie Lips, Debra Perrone, A.J. (Stijn) Reinhard, Scott Jasechko, Tim van der Himst, L.P.H. (Rens) van Beek

Input data used for the calculations and essential output files can be found at: zenodo (doi:10.5281/zenodo.5576446)
Python script to perform calculations can be found at: https://github.com/UU-Hydro/economic_groundwater_limits

Supplementary Methods

Our model to estimate the the maximum depth to groundwater at which groundwater pumping becomes uneconomic combines information from many different domains and sources and represents the data for the year 2015. In many cases, economic data (e.g.,crop prizes, energy costs, GDP per capita etc.) is available at the country level, in which case this information was used directly. For countries where national-scale economic data are not available, data is extrapolated by providing averages of the countries in the same economic region, for which we used the 26 economic regions of the IMAGE model[1]. Tabulated information and resulting input maps can be found in the provided input on the data repository.

Crop water demands and cropped areas

Crop water demands and the corresponding crop area per cell have been computed for the irrigated crops from the MIRCA dataset[2]. For each irrigated crop, the crop area per 5 arcminute cell is extracted and the annual crop water demand per unit irrigated area (m^3 per m^2) computed using the FAO guidelines[3] under the long-term average monthly reference potential evapotranspiration with daily crop factors. The crop water demands are obtained from estimated soil evaporation and transpiration by the crops but is restricted to the growing season, which is defined as that period over which the crop factor is above the minimum crop factor ($kc > kc_{min}$, default value $kc_{min} = 0.20$). This yields net crop water demand, i.e. without losses of irrigation water under conveyance and application (see hereafter). In total, 23 out of the 26 crops of the MIRCA dataset are considered, excluding three categories that are not linked to specific crop types (Supplementary Methods: Table 1).

Supplementary Methods: Table 1. The 26 crops of the MIRCA dataset[2] (crops that are assumed to represent staple crops by us are italicized; these are used to assess uncertainty in average pricing, see herafter). Non-specific crop types (24: others - perennial; 25: managed grassland/pasture; 26: others – annual; all shown in grey) are ignored in this study.

1	*Wheat*	14	Oil palm
2	*Maize*	15	Rapeseed / Canola
3	*Rice*	16	Groundnuts / Peanuts
4	*Barley*	17	Pulses
5	*Rye*	18	Citrus
6	*Millet*	19	Date palm
7	*Sorghum*	20	Grapes and vine
8	*Soybeans*	21	Cotton
9	Sunflower	22	Cocoa
10	Potatoes	23	Coffee
11	Cassava	24	Others (perennial)
12	Sugar cane	25	Managed grassland/pasture
13	Sugar beets	26	Others (annual)

Crop yield and revenue

On a cell-by-cell basis, the crop yield is computed using the water productivity[4] (water use efficiency in agronomical sense; mass of crop yield per volume of water consumed). No distinction in water productivity for rainfed or irrigated crops is made to convert crop water demands into crop yields (Supplementary Methods: Table 2). Equally, variations between cultivars, agroclimatic zones or land management are not considered at the moment, and the value is time invariant.

Supplementary Methods: Table 2. Water productivity[4] (WP, [kg·m^{-3}]) for the different crop types (as numbered in the MIRCA dataset[2]).

Crop type	WP [kg·m^{-3}]	Crop type	WP [kg·m^{-3}]
Wheat (1)	1.15	Oil palm (14)	0.82
Maize (2)	2.15	Rapeseed / Canola (15)	0.99
Rice (3)	0.90	Groundnuts / Peanuts (16)	1.15
Barley (4)	1.18	Pulses (17)	0.55
Rye (5)	1.15	Citrus (18)	8.00
Millet (6)	0.90	Date palm (19)	0.82
Sorghum (7)	1.25	Grapes and vine (20)	3.00
Soybeans (8)	0.75	Cotton (21)	9.81
Sunflower (9)	0.65	Cocoa (22)	1.75
Potatoes (10)	14.0	Coffee (23)	1.75
Cassava (11)	9.00	Others (perennial) (24)[2]	
Sugar cane (12)	9.81	Managed grassland/pasture (25)[3]	
Sugar beets (13)	10.5	Others (annual) (26)	

With the water productivity, the yield per unit area can be computed from the crop water demands (from the FAO guidelines[3]) over the growing season. The yield is then multiplied with the maximum crop area per crop to obtain the total production per 5 arcminute grid-cell for a single year. As the crop water demands currently represent a long-term average, this gives the average expected yield based on the MIRCA crop areas, a representative for the year 2000. Crop production is converted into revenue by taking the price paid to farmers into account. This price is based on the country statistics of FAOSTAT[5] and hence varies per crop and country. The average price (per crop and per country) for the years 1991-2015 was taken as a reference and the price remains constant over time. The average price per crop per region was used if country data were missing.

Irrigation systems: efficiency, distribution and costs

Irrigation systems

To irrigate an area with groundwater, an irrigation system to redistribute and apply the water to the crops, is required in addition to the extraction well. In principle, three types of irrigation systems can be identified[1]:

1) Surface irrigation, including application by flooding and furrows;
2) Sprinkler irrigation, including large-scale pivot systems;
3) Drip irrigation.

[1] Subsurface irrigation is more efficient but is only applied on a very limited scale and is not considered here.

Irrigation efficiency

Since the irrigation methods listed above increasingly require more equipment and labour, they also incur increasing costs and achieve different field application efficiencies. In the case of surface irrigation and sprinkler irrigation, water evaporates once applied whereas soil evaporation is much reduced in the case of drip irrigation when water is applied very localized in space and time. Surface irrigation is often inefficient, as water is applied over the entire area, whereas sprinkler and drip irrigation are applied in a more spatially targeted manner (albeit sprinkler irrigation is subject to interception by the vegetation and subsequent evaporation). All types of irrigation can cause runoff (with decreasing likelihood from surface to sprinkler to drip) but it is assumed that correct application minimizes this loss term. The mean field application efficiencies are listed below[6], together with an indication of a range of reported values. The field application efficiency of surface irrigation is the least efficient and the most variable. Values were based on global studies (Supplementary Methods: Table 3). In all cases, this efficiency is multiplied by 95% to account for the conveyance efficiency for piped water[7].

Supplementary Methods: Table 3. Global values of field application efficiencies per irrigation type. For sprinkler and drip, the characteristic values of Brouwer et al. (1989)[6].have been used directly. For surface irrigation, the field application efficiency was set to 50% given the reported values for the lower and upper value as listed by Jägermeyr et al. (2015)[7] on the basis of their own work and that of Rohwer et al. (2007)[8] and Sauer et al. (2010)[9].

Irrigation methods	Field application efficiency	Lower and upper value
Surface irrigation (border, furrow, basin)	50%	42 - 52%
Sprinkler irrigation	75%	69 - 78%
Drip irrigation	90%	88 - 90%

Applicability of irrigation methods varies with crop type as certain crops cannot withstand prolonged wet conditions (e.g., tropical tubers like cassava) or require completely flooded conditions, as is the case for paddy rice. Furthermore, applicability differs between crops, as a function of profitability (with staple crops such as cereals generally not being eligible for the more costly drip irrigation). Based on these criteria (and for now ignoring soil suitability and topography – included hereafter), each crop type is linked to one, two or three possible irrigation methods (Supplementary methods: Table 4).

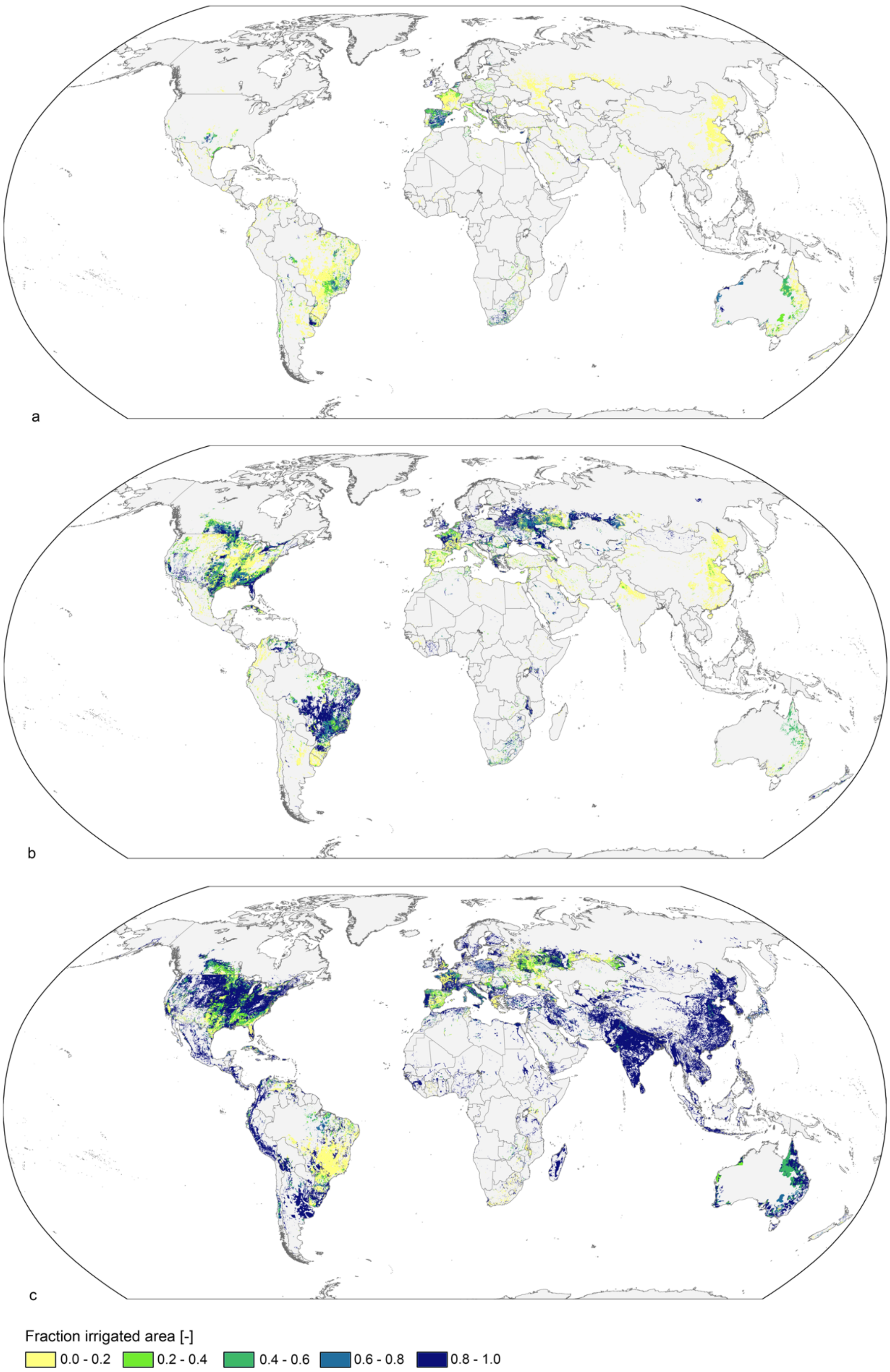
Supplementary methods: Table 4. Crop types and applicable irrigation systems based on the classification of Sauer et al. (2010)[9] and Fischer et al. (2012)[10]. For surface irrigation, B refers to basin, F to furrow irrigation. Sauer et al. (2010)[9] assigned crop systems on the basis of texture; here the most limiting - i.e., best draining - case has been used.

	Crop type	*Surface*	*Sprinkler*	*Drip*
1	Wheat	F	X	-
2	Maize	F	X	-
3	Rice	B	-	-
4	Barley	F	X	-
5	Rye	F	X	-
6	Millet	F	X	-
7	Sorghum	F	X	-
8	Soybeans	F	X	X
9	Sunflower	F	X	X
10	Potatoes [1]	F	X	X
11	Cassava (11)	F	X	X
12	Sugar cane	F	X	-
13	Sugar beets [1]	F	X	X
14	Oil palm	F	-	X
15	Rapeseed / Canola	F	X	-
16	Groundnuts / Peanuts	F	X	X
17	Pulses	F	X	X
18	Citrus[3]	F	X	X
19	Date palm[2]	F	-	X
20	Grapes and vine[3]	F	X	X
21	Cotton	F	X	X
22	Cocoa[3]	F	X	X
23	Coffee[3]	F	X	X
24	Others (perennial) [3]	F	X	X
25	Managed grassland/pasture	B/F	X	-
26	Others (annual) [3]	F	X	X

1 https://cropwatch.unl.edu/potato/plant_growth
2 As oil palms
3 As cotton

Distribution of irrigation types

More efficient irrigation systems are generally more expensive and are likely to be applied to more expensive crops. However, they will require less groundwater to be pumped from fewer wells which would lead to lower pumping costs, partially offsetting the higher investments. Jägermeyr et al. (2015)[7] compiled country information from different sources (AQUASTAT, ICID) and applied it to the crop distribution from LPJml[11] based on applicability scores much like in Supplementary methods: Table 4, applying irrigation systems in the order drip, to sprinkler, to surface incrementally and iteratively to the crops present. This approach is followed here for the MIRCA 2000 dataset[2] with some further adaptations. Eventually, the share of each irrigation system per grid cell (



Supplementary Methods: Fig. *1*) is used to compute the mean irrigation efficiency per grid cell based on the information in Supplementary Methods: Table 3. This ignores the influence of the temporal distribution of crops (length and timing of growing seasons; higher interception losses for sprinkler irrigation during warmer and windier periods) on the weighted average irrigation efficiency. Nonetheless, given the fairly even distribution of irrigation efficiency for the different sources of continental data (cf. Jägermeyr et al., 2015)[7] despite varying crop types, cropping systems and crop calendars, this effect is deemed to be small and well within the uncertainty bounds listed in Supplementary Methods: Table 3.

In this study we start with the country-level information on the share of irrigation systems from Jägermeyr et al. (2015)[7] and redistribute the systems over 5 arcminute cells such that the total area for a system type meets the country total. Here, the same prioritization is given as in Jägermeyr et al. (2015)[7] : first allocating drip irrigation before sprinkler irrigation and that before surface irrigation. Our approach differs from that of Jägermeyr et al. (2015)[7] in the sense that we start from the MIRCA dataset[2] and that we explicitly consider the suitability for an irrigation type based on soil conditions, topography and the crop price. Our distribution is not only a product of a global applicability ranking (Supplementary methods: Table *4*) and the crop distribution but also reflects the variations within the country in terms of feasibility and profitability. In identifying the soil and terrain suitability, we focus on the water-holding capacity and drainage status of the soil as well as terrain slope. Climatic suitability of certain crop types, soil fertility, ease of tilling the soil and toxicity are ignored and assumed to be implicitly covered by the distribution of irrigated crops in the MIRCA dataset. Rules to cover these aspects explicitly were adapted from the GAEZ methodology (Fischer et al., 2012)[10].

Assuming a crop that can be irrigated by all three systems (surface, sprinkler, drip) and postponing the choice whether adapting to more efficient but dearer systems is economically viable, the choice of the type of irrigation system involves the evaluation of the following suitability considerations:

1. Surface irrigation is feasible if sufficient water can be applied with a reasonable frequency to sustain evapotranspiration and thus crop growth over the growing season. This requires that the root zone has sufficient *water holding capacity*. In contrast, sprinkler and drip irrigation will become preferable if the water holding capacity is small and a more frequent application of smaller amounts of water is required to sustain growth.
2. *Low infiltration* rates may become limiting in the case of sprinkler and surface irrigation and drip irrigation (typically applied with a frequency of once every 1 to 3 days at rates of 2 to 20 litres per second) may be preferred.
3. Equally, sprinkler and drip irrigation will become preferable if the drainage rate of the soil is high and applying larger irrigation depths via flooding or furrows would be inefficient as *deep percolation* will remove this water from the root zone.
4. The application of large amounts of water by surface irrigation may lead to stagnating water, which is generally undesirable due to aeration stress (with the exception of paddy rice). So, areas of impeded drainage should be avoided.
5. Surface irrigation requires lower topographical gradients than sprinkler and drip irrigation to avoid losses through runoff. Sprinkler and drip irrigation can be applied therefore in sloping terrain although this of course would incur additional costs for contouring, terracing etc.

To evaluate these criteria, topographical information from the GTOPO30 data[12] is used to evaluate the topographical gradients. Soil information is taken from S-World[13] for the present-day situation. Both datasets are available at 30 arcseconds and, after evaluation of suitability at 30 arcseconds, average suitability is calculated for 5 arcminute cells. In the case of S-World, the soil conditions for cultivated areas are considered separately if present in the corresponding land cover mask that was derived from the GLOBCOV[14] dataset. In case GLOBCOV finds no cultivated land in 5 arcminute cells of MIRCA that are identified as having irrigated agriculture, it is assumed that the entire MIRCA 5-arminute cell is cultivated.

This information is then evaluated in relation to a generic irrigated crop which is assumed to have a crop water demand of 1000 mm over a growing season of 100 days that is irrigated by a weekly schedule (14 weeks = 98 days at which 1000 / 14 = 71 mm is applied), typical of surface irrigation by flooding. Equally, the root depth is assumed to be 1000 mm and in this root zone all irrigation water should be stored and buffered. We acknowledge that using these generic crop parameters to test suitability for a given irrigation type is a crude assumption, but the chosen values are characteristic for most annual crops that have growing seasons of 90 to 150 days and include a ripening phase during which irrigation ceases. A crop water demand of 1000 mm over the growing season is at the high end but not uncommon and in line with the assumption of this study that the crop water demands have to be completely met from irrigation water. In the soil suitability assessment, we further assume irrigation to be 100% efficient.

We quantify the 5 suitability considerations laid aout above by evaluation of 4 suitability criteria S_i for surface irrigation, with a value of 1 for maximum suitability and 0 for no suitability (such that drip or sprinkler irrigation should be considered). These criteria are 1) S_1 slope 2) S_2 soil water holding capacity; 3) S_3 infiltration rate ; 4) S_4 percolation rate. In the overall assessment we consider the suitability criteria equally important and derive the overall suitability by:

$$\widehat{S} = \left(\prod_i^n S_i \right)^{1/n} \tag{1}$$

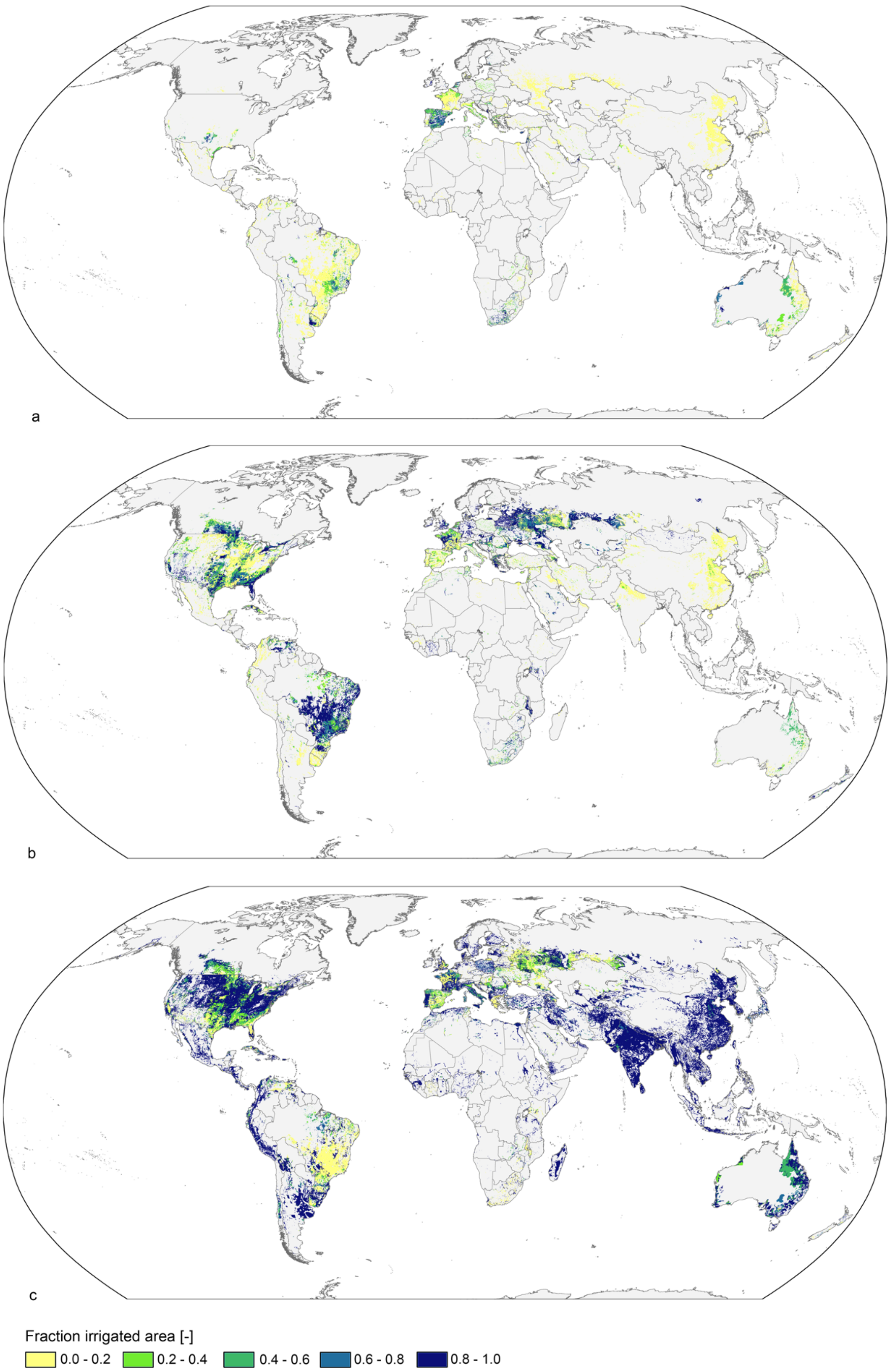
A zero *slope* (criterion 1) gets a suitability of 1 for surface irrigation and a slope of 7% or higher a suitability of 0. Also, sprinkler irrigation is demed only suitable for slopes less than 15% (see herafter).

Starting from the weekly schedule for surface irrigation, the corresponding *soil water holding capacity* (criterion 2) of the root zone can be computed, taking the total effective pore space of the root zone and the relative degree of saturation at field capacity and wilting point into account (respectively matric suction heads of 3.3 and 150 m respectively; using the soil water retention curve of Clapp and Hornberger (1978)[15]). Following FAO guidelines[3], irrigation would occur if the total available water content (taken here equal to the water holding capacity) is around 70% depleted. This means that the water holding capacity should be 143% of the scheduled irrigation amount of 71 mm, i.e., 102 mm. In case the water holding capacity is lower than this, drip or sprinkler irrigation should be considered if applicable (Supplementary methods: Table 4). Suitability for the water holding capacity is then defined as the ratio of the default irrigation frequency of 7 days and the higher frequency necessary in case the water holding capacity becomes limiting.

Surface irrigation water is applied over relatively short periods (up to 48 hours) and the infiltration rate should be considered to ensure that the applied water can be accommodated and the amount of water lost to evaporation is limited. On the other hand, if infiltration rate is enough, deep percolation may be prohibitively large such that the applied water is inaccible to roots. Thus, criteria 2 and 3 need to be balanced; the infiltration rate should be large enough to accommodate the water applied at the surface and the percolation rate sufficiently low to prevent excessive drainage from the root zone (criterion 3).

For the *infiltration rate* (criterion 2), we use the saturated hydraulic conductivity of the top layer and consider two conditions for the infiltration rate: (i) the limiting case that the applied irrigation water depth (crop water demand over the irrigation frequency) infiltrates over the total irrigation interval (default values of respectively 71 mm and 7 days), and (ii) the more favourable case that all applied infiltration water infiltrates within one day. The first case would result in a suitability of 0, the latter to a suitability of 1 where the infiltration rates in between are scaled logarithmically.

For the *percolation rate* (criterion 3), a characteristic rate is defined here as the mean hydraulic conductivity under fully saturated conditions and field capacity using the relation between matric suction and the relative hydraulic conductivity of Campbell (1974)[16]. For the vertical flow through the root zone, the harmonic mean of the percolation rate of the top soil (0.30 m) and the remaining subsoil (0.70 m) is used. As long as the irrigation schedule for surface irrigation remains proportional to the water holding capacity as outlined above, the fastest rate at which the available water can drain is 71 mm over 7 days or a rate of $1.02 \cdot 10^{-2}$ $m \cdot day^{-1}$. Generally, percolation rates will be lower than this limit and soil moisture becomes exhausted by evapotranspiration. However, hydraulic conductivity may be larger than this limit in which case losses due to deep percolation can become significant and application by surface irrigation inefficient. To address this effect, the estimated percolation rate is scaled logarithmically between this limit and a rate 10 times as large to span the suitability range from one to zero (approximately $1.02 \cdot 10^{-2}$ and $1.02 \cdot 10^{-1}$ $m \cdot day^{-1}$ respectively for the default case); thus, lower percolation rates will identify situations in which surface irrigation is permissible (suitability approaching 1); at higher rates, sprinkler and drip irrigation will become preferable (suitability approaching 0).



Supplementary Methods: Fig. 1. ***Fractional contribution per cell of the irrigation type*** *(from top to bottom: (a) drip, (b) sprinkler and (c) surface) based on the MIRCA[2] crop distribution, the suitability per crop of Supplementary methods: Table 4, soil properties[11], topography and the country areas listed by Jägermeyr et al. (2015)[7]. Cells for which an irrigation type is absent are in grey.*

In summary, starting with the country-level information on the share of irrigation systems of Jägermeyr et al. (2015) [7], our approach is to first assign drip irrigation to the fractions of crop types within 5 arcminute cells with the highest price (USD kg^{-1}), while limiting the allocation to those crop types for which the irrigation type is applicable (Supplementary Methods: Table 4) and preferentially allocating to cells where the suitability for surface irrigation is the lowest. Next the same procedure is followed for sprinkler irrigation, of course not including those cell fractions that have already been allocated to drip. Also, for sprinkler only locations with slopes less than 15% are used. The remaining crop fractions of the remaing cells are assigned to surface irrigation.

Cost of above ground irrigation infrastructure

The costs of above ground irrigation structure per irrigation type have been compiled from the agricultural literature for the USA[15] (Supplementary Methods: Table 5). These costs have been scaled per country based on the ratio of gross domestic product per capita (GDP $capita^{-1}$) for the country and the US GDP $capita^{-1}$ and thus are assigned at country level. Typical depreciation periods for irrigation systems listed range between 25 and 35 years. A value of 30 years is used that is identical to that used for the groundwater wells.

Supplementary Methods: Table 5. Installation costs per irrigation type for the USA in USD per hectare (based on [15])

Irrigation methods	Costs [USD $.ha^{-1}$]
Surface irrigation (border, furrow, basin)	568
Sprinkler irrigation	1165
Drip irrigation	2795

Calculating required pump capacity, pumping efficiency with depth and pump costs

Different pump types are available having different operation ranges in terms of total dynamic head, pump capacity and efficiency. Considerations to select an efficient pump and to factor in day-to-day variations in pump speeds or water levels are manifold and are beyond this more general analysis. As the focus is here on deep wells, two pump types are selected:

- Centrifugal pumps that are applicable in wells from 10 m depth until 100 m depth and deliver discharge rates up to 100 litres per second (8,640 m^3/day);
- Deep-well turbine pumps that operate in wells up to 1000 m deep and can provide comparable pump rates.

These types of pumps are not as efficient as propeller-type pumps that are commnly used at shallow depths (less than 20 m) and require more investments as they are permanently installed in cased wells. Submersible pumps are another alternative but their range of operation is comparable and they become more expensive to operate than centrifugal pumps or deep-well turbine pumps in deeper wells and at higher flow rates.

The efficiency of pumps depends first on the type of engine and secondly on how efficiently this energy is transformed via the transmission, etc. into extracted water. As a result, the overall efficiency is a function of the pumping rate, the speed of the pump during operation and the depth at which water has to be extracted. In the case of deep-well turbine pumps, water can be extracted at greater depths by stacking vertical elements or *stages* that house an impellers in a pump bowl. Efficiency of a deep-well turbine pump then varies with the head that that each stage covers and the size of the impeller, which in turn define the required power and the discharge that can be supplied. This assembly of a deep-well turbine pump with multiple stages requires more investment and maintenance, making them more expensive to install than centrifugal pumps. Compared to centrifugal pumps, deep well turbine pumps, however, are more energy efficient. Overall, pumping efficiencies are complex (e.g., Scherer, 201716) and there is no clear-cut way to compute the costs of acquisition and operation per pump. Here, pumping capacity and pump installation costs are computed in the following generalized way:

1. The pump capacity is fixed at a uniform rate (771,000 $m^3.year^{-1}$);
2. The actual pump efficiency is first and foremost a function of the head difference that needs to be overcome by the pump; this is set based on the pumping efficiencies of Scherer (2017)[16] and takes the general form of:
   $$\epsilon_z = \epsilon_i + (\epsilon_f - \epsilon_i)(1 - e^{-z/z_{ref}}), \quad (2)$$
   where ϵ_z is the (unitless) pumping efficiency [-] at the head difference z [m], z_{ref} is a reference head difference [m], and ϵ_i and ϵ_f are the initial and final pumping efficiencies [-]. Based on the information of Scherer (2017)[16], the reference head difference is set to 180 m and the initial and final efficiencies at respectively 0.950 and 0.600, which means that the efficiency at the reference head difference becomes ~ 0.700.
3. When new investments are considered, the efficiency is computed using the projected water depth in the well and any overpressure needed (see below) at the end of the investment period. The projected well depth depends on the total groundwater extraction over the period and this negatively affects the estimated pump efficiency of (2) and thus raises the number of pumps that is required to satisfy the total irrigation water requirement in a 5 arcminute gridcell. Based on data compiled by Almas et al. (2010)[15], the relation between the required power of the pump and the costs are relatively independent of the pump type, albeit different pump types cover different head ranges. The relationship can be described by a linear function where the intercept represents the fixed installation costs [USD] of the pump and the slope [$USD.kW^{-1}$] the variable component dependent on the head difference over which the extracted volume has to be pumped and the overpressure (expressed in potential energy). These components were estimated at 30,000 USD and 150 $USD.kW^{-1}$ respectively and this explains 76% of the variance in the pump price in relation to the extracted volume and the head difference for the USA. These values have been scaled based on the ratio of GDP $capita^{-1}$ per country and US $GDP.capita^{-1}$ and are thus assigned at country level.

Calculating required overpressure

Sprinkler irrigation systems require additional overpressure to operate the sprinkler and cover the irrigated area. Under the assumption that water leaves the sprinkler at ground level (y = 0 m) and experiences no resistance when passing the sprinkler and passing through the air, the water will follow a parabolic trajectory. This trajectory has a constant horizontal velocity component and a variable vertical velocity component due to the gravitational acceleration. The position of water in the jet will consequently vary in time:

$$v_x(t) = v_{x_0} = v_0 \cos\alpha, \qquad x(t) = v_{x_0} t, \tag{3}$$

$$v_y(t) = v_{y_0} - gt = v_0 \sin\alpha - gt, \qquad y(t) = v_{y_0} t - \tfrac{1}{2} g t^2. \tag{4}$$

Here, α is the angle at which the jet leaves the sprinkler.

Since the horizontal velocity [$m.s^{-1}$] is constant, the time required to cover a pivot of radius R [m] on level ground can be computed from $t = R/v_{x_0}$, at which time the elevation of the jet should be equal to the ground level again:

$$\begin{aligned} & y(t) = v_{y_0} t - \tfrac{1}{2} g t^2 = 0 \rightarrow \\ & v_{y_0}\left(R/v_{x_0}\right) - \tfrac{1}{2} g \left(R/v_{x_0}\right)^2 = 0 \rightarrow \\ & v_0 = \sqrt{\frac{gR}{2\sin\alpha\cos\alpha}} \end{aligned} \tag{5}$$

The system would be at its most efficient if the denominator in the root is at its highest value. This is obtained if α = 45°, in which case $\sin 45° \cos 45° = \tfrac{1}{2}\sqrt{2}\,\tfrac{1}{2}\sqrt{2} = \tfrac{2}{4} = \tfrac{1}{2}$. In that case, the ejection velocity becomes:

$$v_{0min} = \sqrt{gR} \text{ for } \alpha = 45° \tag{6}$$

Under the assumption that Bernoulli's equation holds and energy is conserved, the pressure required on top of the elevation potential of the well depth *z* is equal to:

$$-z + \frac{P}{\rho g} + \frac{0^2}{2g} = 0 + \frac{0}{\rho g} + \frac{{v_{0_{min}}}^2}{2g} \tag{7}$$

Here, P is the total pressure head [Pa] that is needed to withdraw water from the well and give it the required initial velocity to cover the radius that is covered by the sprinkler. Thus, the total pressure required becomes:

$$P = \tfrac{1}{2} \rho {v_{0_{min}}}^2 + z\rho g = \tfrac{1}{2} \rho g R + z \rho g \tag{8}$$

This results in an overpressure $p_S = \frac{1}{2}\rho g R$. Large-scale sprinkler systems ('big gun systems') cover areas radii in the order of 50 to 100 m under high pressure (600 to 900 kPa[19]). This would correspond to an overpressure of 250 to 500 kPa under the idealized conditions considered here. For sprinkler systems, a radius of ~100 m is used here, meaning an overpressure of 500 kPa. In the model, heads are defined in [m] and the overpressure is converted accordingly in the computations.

Other irrigation systems than sprinklers still require overpressure to distribute water over a field and to overcome resistance during transport[20]. For surface irrigation and drip irrigation, here uniform correction factors of respectively 30 and 50% are used relative to the overpressure of sprinkler irrigation (100%).

Energy costs

The total head difference due to the falling groundwater level relative to the surface and the overpressure necessary to distribute the irrigation water over the surface relates directly to the energy costs. In this instance, all pumps are assumed powered by electricity, which must be bought at a fixed price per unit [$USD.kWH^{-1}$]. Here, country data on the electricity price were retrieved from the Organisation for Economic Cooperation and Development (OECD)[21], which was supplemented with Eurostat data[22]. This combined dataset covered 63 countries over the period 2009 – 2017 and included the prices for non-household users. First, all prices were converted to USD using appropriate conversion rates. For the countries for which the data between the two datasets overlapped, the highest price per year was selected and the average price over the available years computed.

For the countries with missing data, a relationship with GDP per capita was explored[23–25], but this did not provide a clear, predictive equation and, therefore, regional averages of the electricity price per region were used instead.

The use of electricity prices overlooks, of course, the fact that energy can be provided by other sources (fuel, solar and wind etc.) or that energy costs for agricultural puposes may be subsidized in certain countries, which is, unless implicitly included in the global datasets, not accounted for. Notwithstanding, electricity is the dominant energy source for irrigation in many countries and will provide a conservative estimate to the economic limit in case less expensive energy sources are used.

Well construction costs: labour and material

Investment costs for well construction include labour costs and material costs for drilling, the placement of casing and testing. These costs can be related to the depth of the well and do not explicitly include maintenance costs for the irrigation infrastructure and the well after construction.

Costs for irrigation wells were taken from [PSU, n.d.][26] and deemed representative for the USA. Costs were corrected for the fixed costs for the pump and its placement and standardized for the listed well depth. This gives a rate of 967 $USD.m^{-1}$ for labour costs and 300 $USD.m^{-1}$ for material costs. Thus, the construction costs of a single well of 150 m deep would amount to a total of 190,000 USD, to which the costs for the pump and electric installation as well as the above ground irrigation infrastructure should be added.

To extrapolate the labour costs globally, information on the hourly compensation for labour from 35 countries were obtained from the US Bureau of Labor Statistics (2012)[27]. This covers a full range from high income countries (e.g., Australia, Belgium and the USA) via middle income countries (e.g., China) to lower income countries (e.g., India, Philippines). A strong power relationship exists between the reported wages and the GDP per capita ($R^2 = 0.918$) and this has been used to estimate the labour cost for all missing countries.

For the material costs, the same relation is used, assuming that a direct relationship exists between wages, purchasing power and prices. Consequently, in India, this gives a rate of 28.67 $USD.m^{-1}$ for labour costs and 8.90 $USD.m^{-1}$ for material costs. Thus, the construction costs of a similar single well of 150 m deep would amount to a total of 5,640 USD. Note that for the material costs, the relationship is less strong and adds substantial uncertainty in estimating the costs in determining the economic limit for groundwater-fed irrigation.

There are some other sources of uncertainty in the material costs, one being the fact that the well prices used to estimate the costs per metre are relatively old and from a single source. However, a comparison with other documents on drilling costs from the USA indicate that it is in the correct order of magnitude. Another factor of uncertainty is the parent material in which the well is drilled, which in this case concerns alluvial material. Drilling costs that are specified per material type show that drilling costs can vary widely with the material involved. However, it is difficult to take that into account in a global analysis for three reasons: (i) the within-variability for drilling costs per lithology class is large and often overlaps with other classes; (ii) drilling costs may increase in more troublesome lithologies (and decrease in easier materials) but it is difficult to separate this into a labour and material component; and, (iii) information on the local lithology, vertical stratification and actual rock mass quality is not provided by data sources on global lithology and the additional work is, therefore, possibly not warranted by the added uncertainty if specific costs per lithology type were taken into consideration. Apart from lack of lithological data, there is an additional argument for using uniform labor costs for drilling: there may be an inverse relationship between drilling costs and the costs of lining and maintenance. The harder the parent material, the less lining and maintenance costs and vice versa.

Interest and discount rate

In our analysis, the economic limit to groundwater-fed irrigation depends on the interest rates of the loans that are taken out to pay for the investments and the discount rates that determine the present value of future costs and revenues from irrigated crops. Information on the interest rates from 123 countries for the year 2016 was retrieved from the World Bank[28]. Of these countries, 11 had negative interest rates. Furthermore, we assumed interest rates for loans to be two percent higher than the discount rate in each country. With this difference, 27 countries resulted in a negative discount rate and those instances, the discount rate was set to the default value of 1% and the corresponding interest rate to 3%. For those countries for which the discount rate and the interest rate were missing, the regional average was used. If no data was available, the global average was assigned to the country (7.42% and 9.42% for the discount rate and the interest rate respectively).

First-order second-moment analysis

To evaluate the uncertainty in the maximum economic groundwater depth and its associated variables, we performed a first-order second moment analysis in which we varied the input parameters with a higher and lower value, of which we took the range to be equivalent to two times the standard deviation:

$$\sigma \equiv \frac{x^+ - x^-}{2} \qquad (9)$$

So,

$$x^+, x^- \cong \bar{x} \pm \sigma \qquad (10)$$

Typically, these lower and upper values are defined with respect to the mean and can be set through addition or multiplication, respectively:

$$x^+, x^- = \bar{x} \pm \Delta x \qquad (11)$$

$$x^+, x^- = (1 \pm f)\bar{x} \qquad (12)$$

The first (additive) formulation is preferred for globally uniform parameters, the second (multiplicative) formulation for parameters that vary per country and can have very different magnitudes. Here, f can be considered equal to the coefficient of variation (*COV*).

Discount and interest rate

As mentioned above, a fixed difference of 2% between the discount and interest rate was assumed and that the discount rate (and interest rate) cannot be negative. Thus, the same additive range was assumed for both parameters. Data on the interest rate from the World Bank over the period 1961-2020 show large variations. Focusing on high income countries, where loans are widely available from established financial institutions, the interest rates vary by a few percent around the long-term mean. For example, for the USA, the standard deviation over the entire period is 2.2%. In order to avoid for the discount rate negative values on the lower end, additive changes were used and the negative change Δx^- was set to 0.5% and the positive change Δx^+ to 3% relative to the country-specific discount rate and interest rate.

Material and labour costs

For the material and labour costs, a symmetric multiplicative factor was applied in the First-order second-moment analysis (FOSM) that applies to the country-specific value. Variation in the material costs is applied not only to the material costs per depth but also to the costs that are involved in acquiring and installing the pump and the irrigation infrastructure; variation in the labour costs only affects the costs to drill, line and test the well as described above. Variation was estimated from the reported wages for the 35 countries relative to the fitted relationship and shows an estimated coefficient of variation of 0.20 [-]. For the material cost, the same approach is followed but -quite arbitrarily- the coefficient of variation is increased to 0.25 [-] to account for the fact that the uncertainty in the drilling costs has to be added to this and the relationship to the wages is less direct.

Energy costs

For the energy costs, the absolute difference between the regional estimate and the reported value for the 63 countries were used. The absolute difference was normalized by the reported value and the resulting number considered to be equal to the coefficient of variation. These country values were then averaged, giving an average ratio of 0.129 [-]. Hence, a value of 0.13 was adopted for the *COV* in the FOSM.

Crop prices

The model can be expected to be relatively sensitive to the crop prices as they determine the revenue. In order to obtain a reasonable estimate of the 30 year variation in crop prices, the following was done:

1. Indexed annual (producer) prices (average 2014-2016 = 100%) were downloaded from FAO FAOSTAT[5] for all countries in the world over the period 1991-2019 for eight staple crops: wheat, maize, rice, barley, rye, millet, sorghum and soy beans;
2. For each country, the available time series was fitted with an exponential relationship and the R^2 reported. The fitted function was then used to determine the deviations of the reported prices relative to the fitted trend in order to remove any bias.
3. From these deviations, the average absolute value was retrieved;
4. Data were further processed if the R^2 of the fitted trend line per crop type was above 0.25 for each country.
5. In that case, the relative areas, i.e. the ratio of the crop area of the country under consideration and the total available crop area (for which $R^2 \geq 0.25$), was determined and multiplied by the squared average absolute deviation.
6. The sum of the squared average absolute deviations times the relative areas (an area weighted average) is considered to be representative of the relative variance of the crop prices and the square root taken to get the coefficient of variation (*COV*).

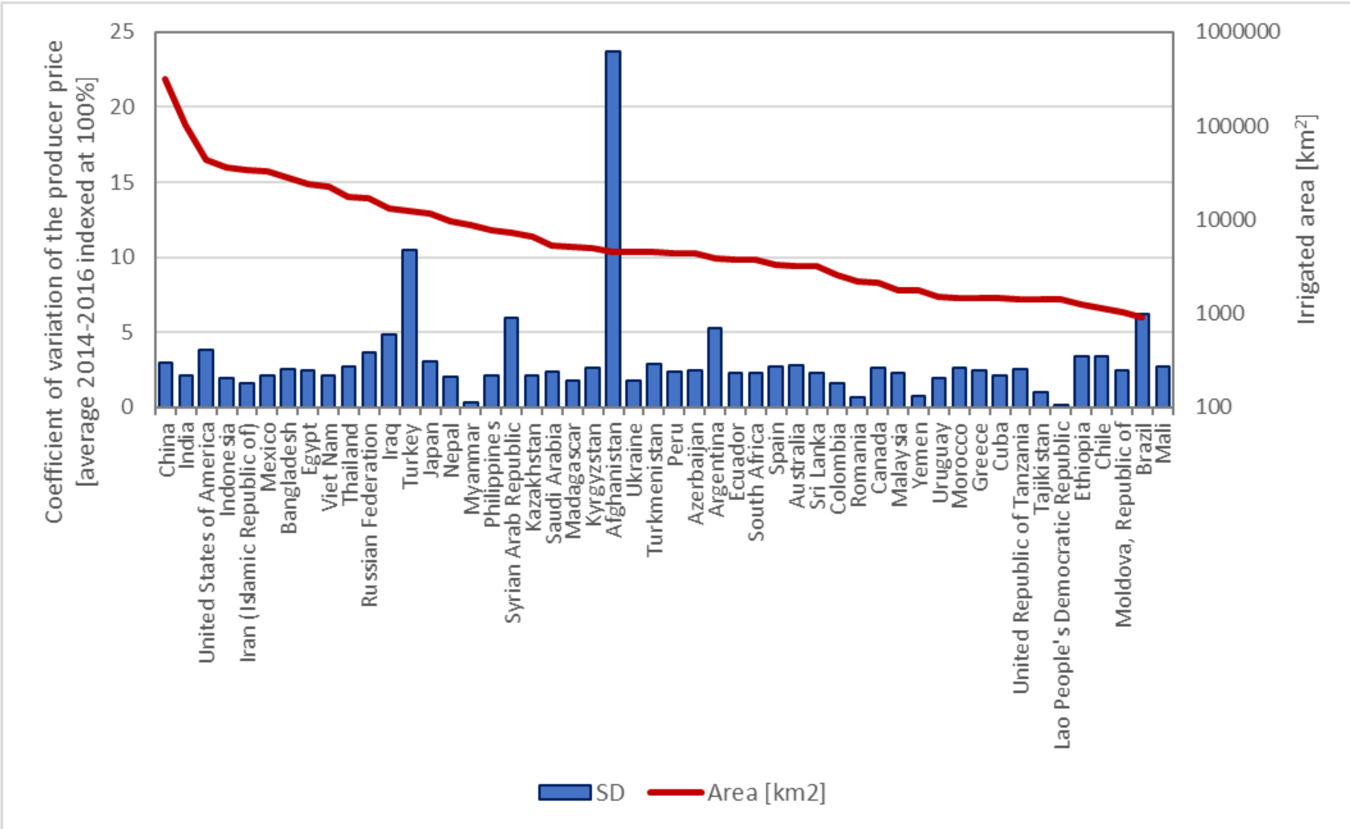
This procedure ensures that a relatively large sample of countries, crops and years is taken into consideration and the use of the crop area and the indexed crop price for the eight staple crops results in a globally representative value. In order to exclude the influence of hyperinflation on the prices, data from Venezuela and Zimbabwe were excluded. This procedure is relatively robust, with the COV changing little if the limit to select areas on the basis of the R^2 remains below 75%.

Overall, the representative COV is estimated to be 3.2% relative to the indexed crop price of 100%. In order to be conservative, a symmetric value of 5% (0.05 [-]) is used in the FOSM for all crops in all countries at the same time.

While great care was taken to include a large sample of prices over many countries, the data are still slightly biased towards the data of richer countries and cash crops are not taken into consideration explicitly. Moreover, the variance is weighed by the crop area and not by the yield or revenue. However, by selecting staple crops, differences in yield or revenue are considered to be less important and the estimated COV relatively unbiased. In order to show the variation in the estimated COV and the crop area, the 50 countries with the largest irrigated area for staple crops are shown (Supplementary Methods Fig.).

Pumping efficiency

Pumping efficiency varies widely and its variation is hard to quantify without detailed information on the pump type, the head difference and the pumping rate, which cannot be specified in a global model. Hence, to include the variation in the pumping rate, additive changes to the initial and final pumping efficiencies are applied at the same time. The pumping efficiency cannot exceed unity and the prescribed initial pumping efficiency is 0.950 [-] whereas the maximum efficiency from nomogrammes[17] is 0.985. On the lower end, the prescribed final pumping efficiency is set to 0.700 whereas typically the lowest efficiencies shown are in the order of about 0.600. Thus, the pumping efficiency in the FOSM is increased by 0.025 and decreased by 0.100.



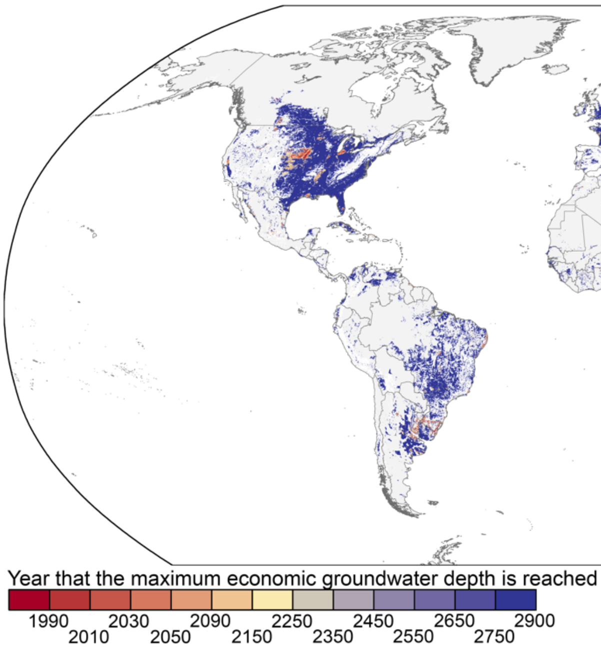
Supplementary Methods Fig. 2. Country average COV (ratio of average standard deviation relative to the indexed crop price) and corresponding crop area, totalized for eight staple crops, for the 50 countries with the largest irrigated area for these crops

Hydrogeological information

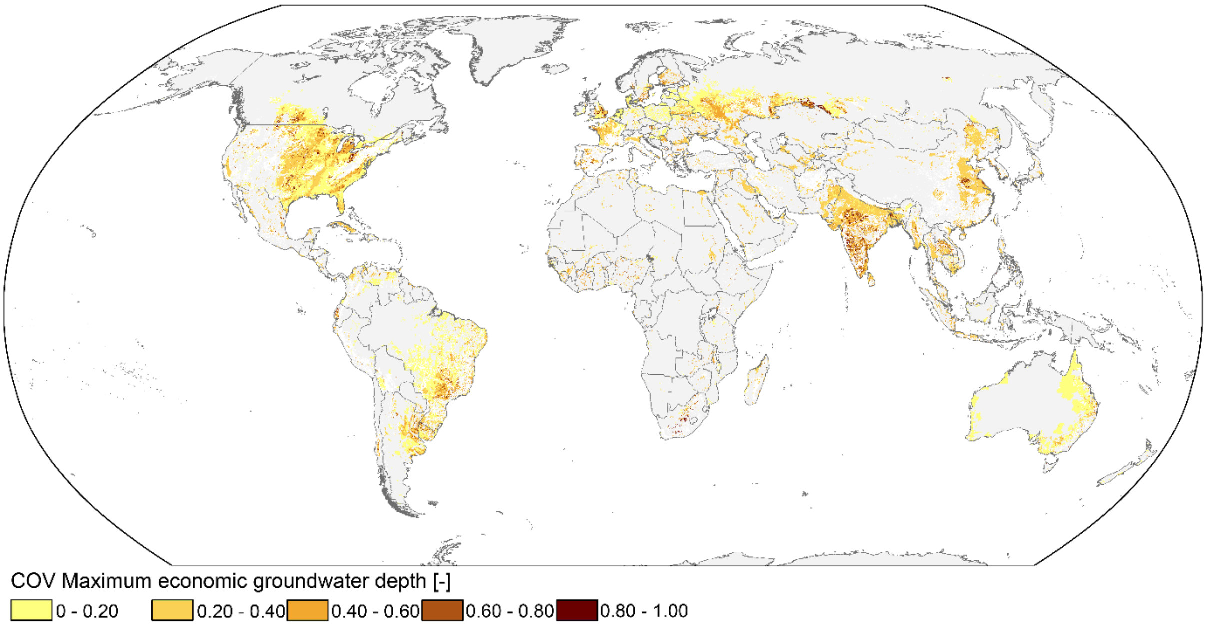
Hydrogeological information concerns the aquifer from which the water is drawn and the confining layer that may be present. The presence and thickness of the aquifers and the confining layers are based on De Graaf et al. (2017)[27], with 20% of the aquifer area covered with a confining layer. The thickness of the aquifer is not directly considered in the model but the confining layer influences the well depth as this non-productive layer has to be perforated before groundwater can be extracted efficiently. In this case, the extent of the confining layer is fixed but its thickness varies in the FOSM with a COV of 10% symmetrically around the mean.

For the specific yield of an unconfined aquifer, information from the GLHYMPS dataset[29] is used. Here, a symmetric relative change around the mapped effective porosity at 5 arcminutes is used which is averaged from the mapped lithology at 30 arcseconds. For the confined aquifers, a similar variation is considered to describe the falling head if water is initially extracted under confined conditions; here a global mean storativity of 0.001 [$m.m^{-1}$] is considered, as used by De Graaf et al. (2017)[30], but the variation considers separate lower and upper boundaries that are based on the variation from the effective porosity for the underlying aquifer, assuming a lognormal distribution of the storativity. Thus, both the effective porosity and the storativity have a coefficient of variation that is fully spatially distributed.

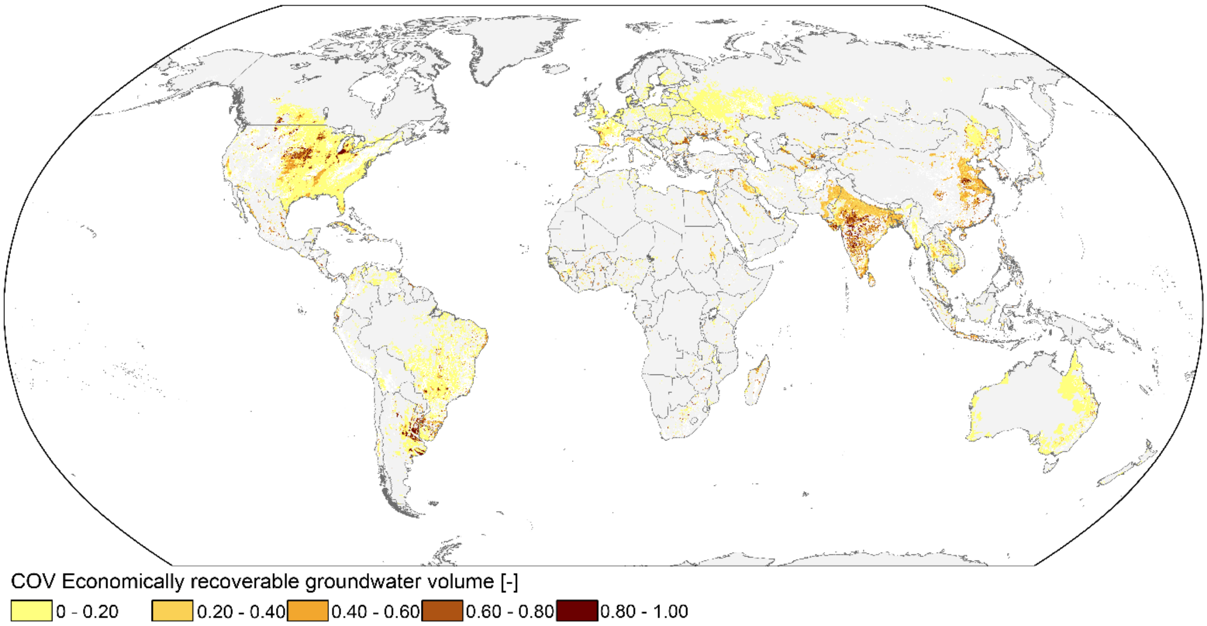
Supplementary Figures



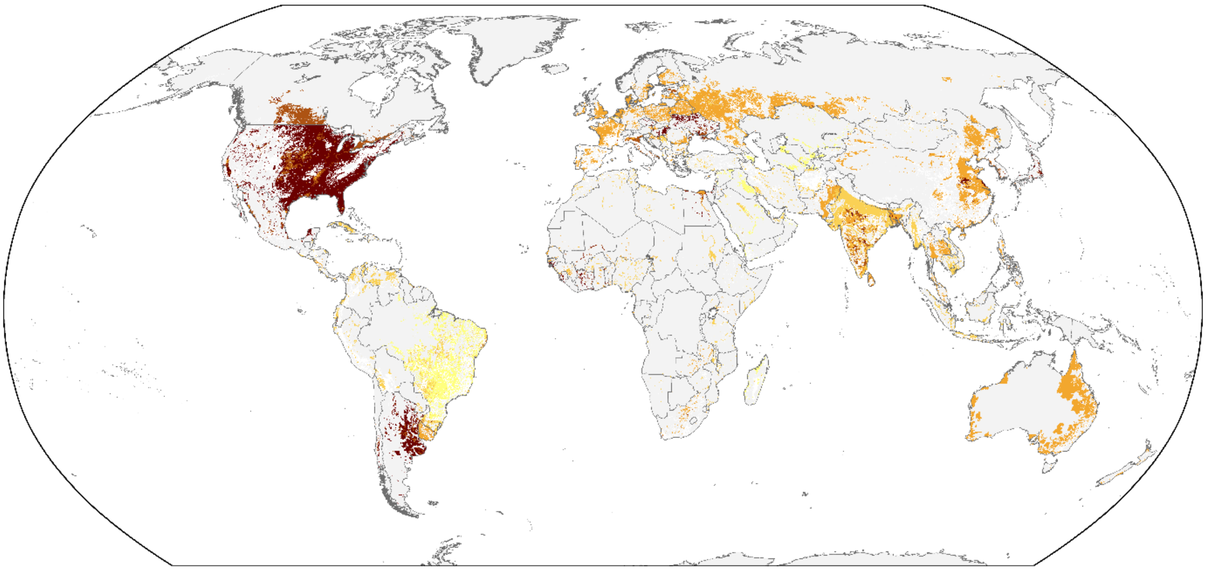
Supplementary Figure 1. Year that the maximum economic groundwater depth is reached after starting pumping and well deepening from 1970. Note that this is not a projection of actual timing of reaching the economic limit, but a representation of the rate towards reaching the economic limit under the scenario that all irrigation water comes out of groundwater storage. Cells for which no irrigated agriculture is present or maximum economic value is not reached before 2900 are in grey



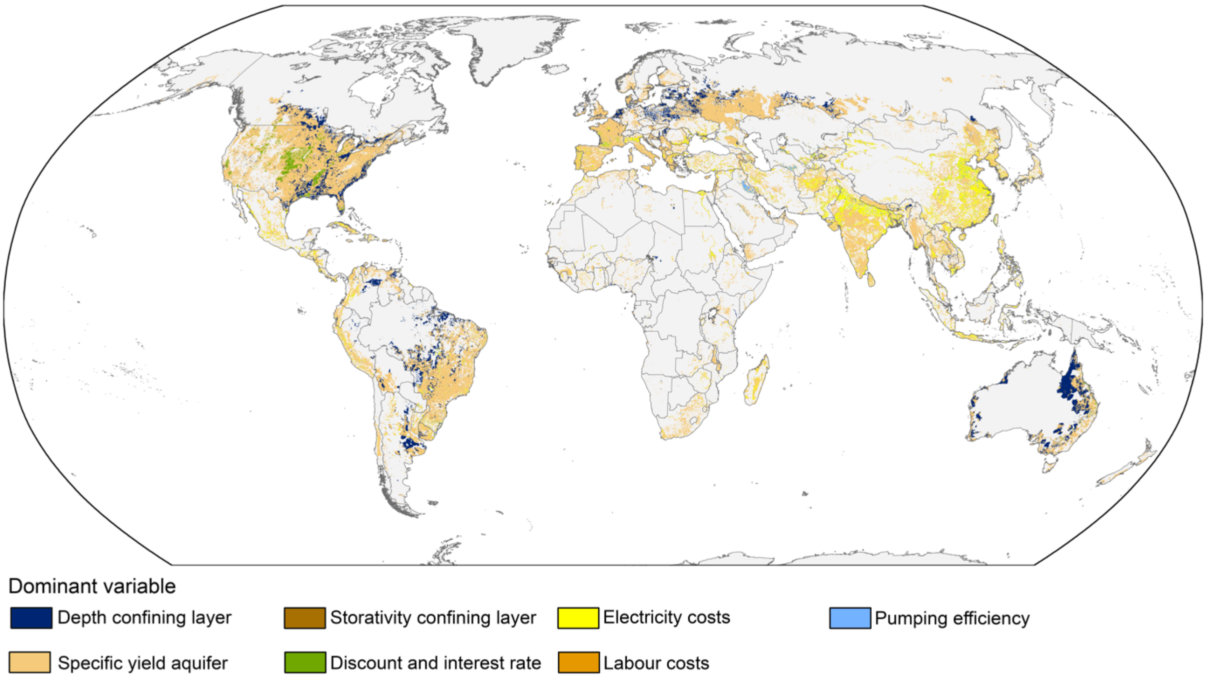
Supplementary Figure 2. Uncertainty in maximum economic groundwater depth (error standard deviation as a fraction of estimate) obtained by a first-order-second moment analysis (see Methods); cells for which no irrigated agriculture is present are in grey.



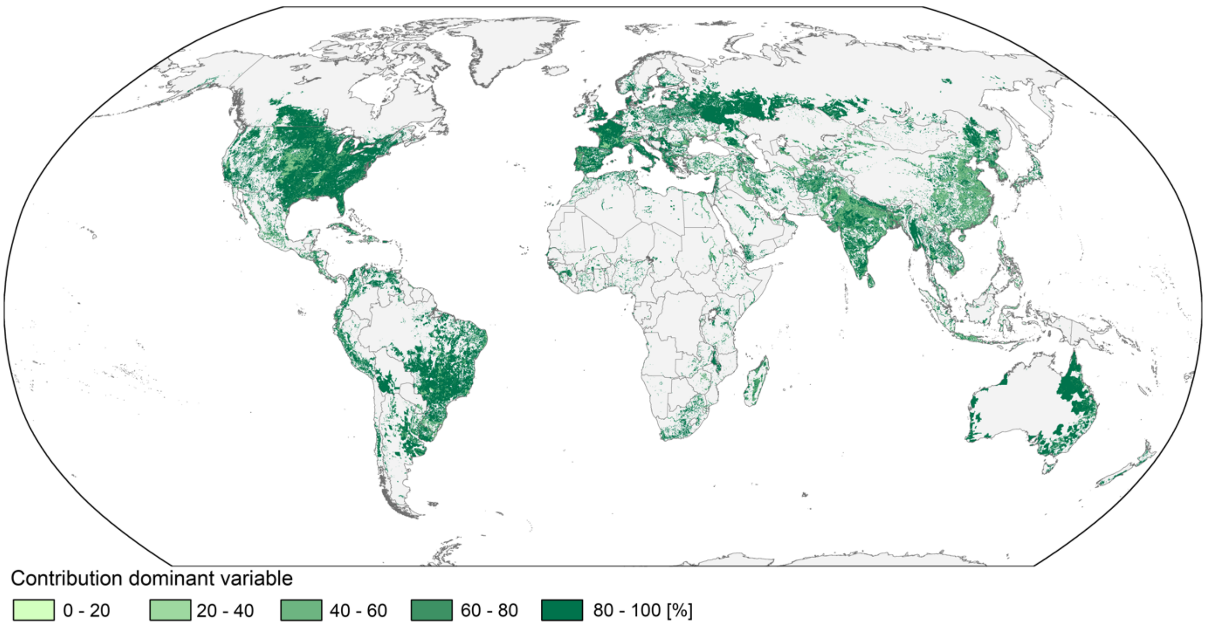
Supplementary Figure 3. Uncertainty in estimated depth of groundwater that can be withdrawn until maximum economic groundwater depth (error standard deviation as a fraction of estimate) obtained by a first-order-second moment analysis (see Methods); ; cells for which no irrigated agriculture is present are in grey.



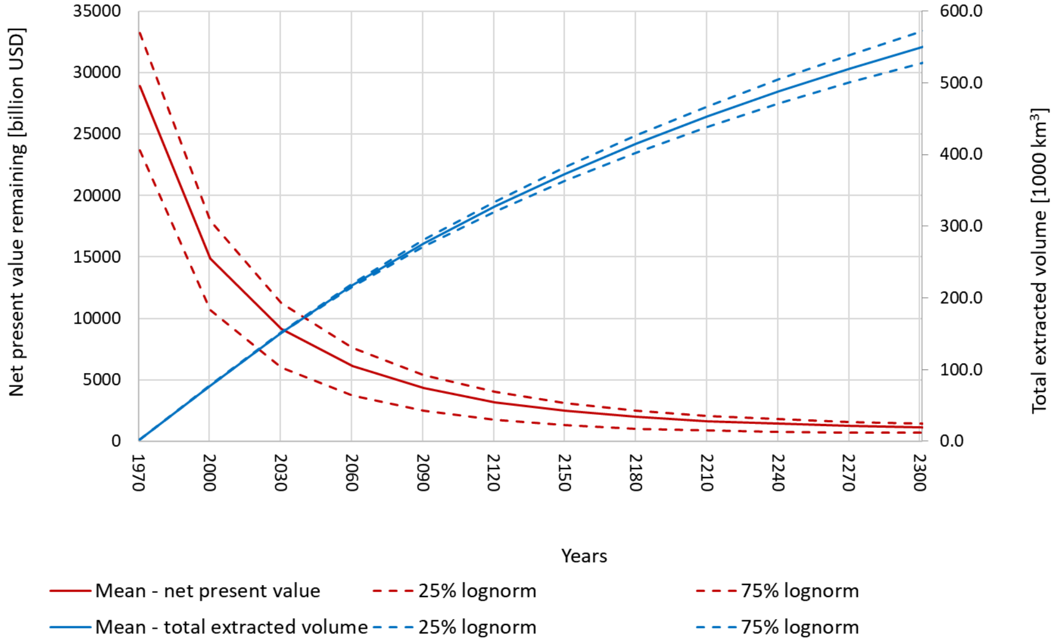
Supplementary Figure 4. Uncertainty in net present value of economically recoverable groundwater (error standard deviation as a fraction of estimate) obtained by a first-order-second moment analysis (see Methods): ; cells for which no irrigated agriculture is present are in grey.



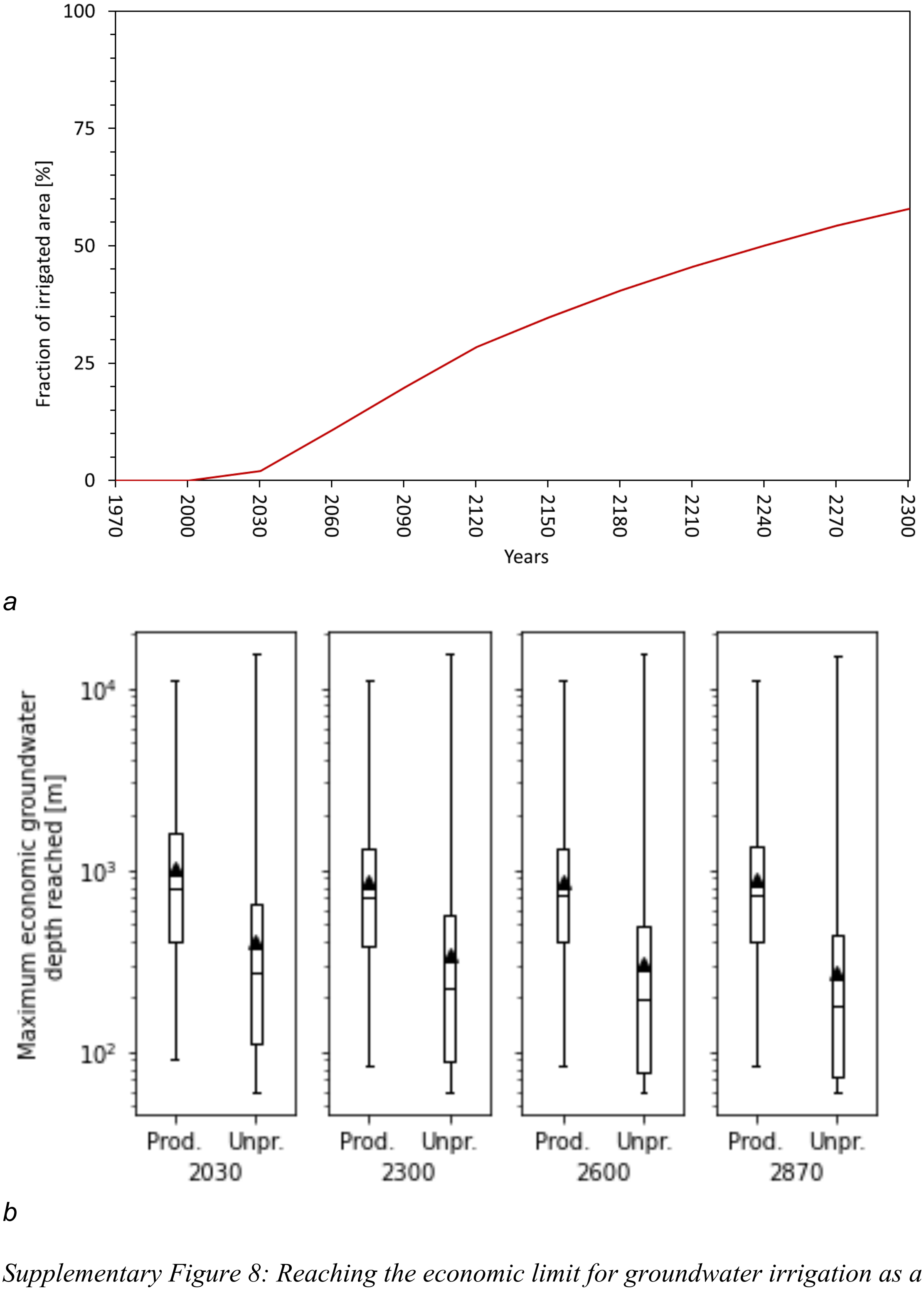
Supplementary Figure 5. Dominant variable contributing to the uncertainty in estimated maximum economic groundwater depth (in terms of variance). In total nine variables were included in the uncertainty analysis (Supplementary Table 3), but two are absent from the dominant variables (material cost and crop price); cells for which no irrigated agriculture is present are in grey.



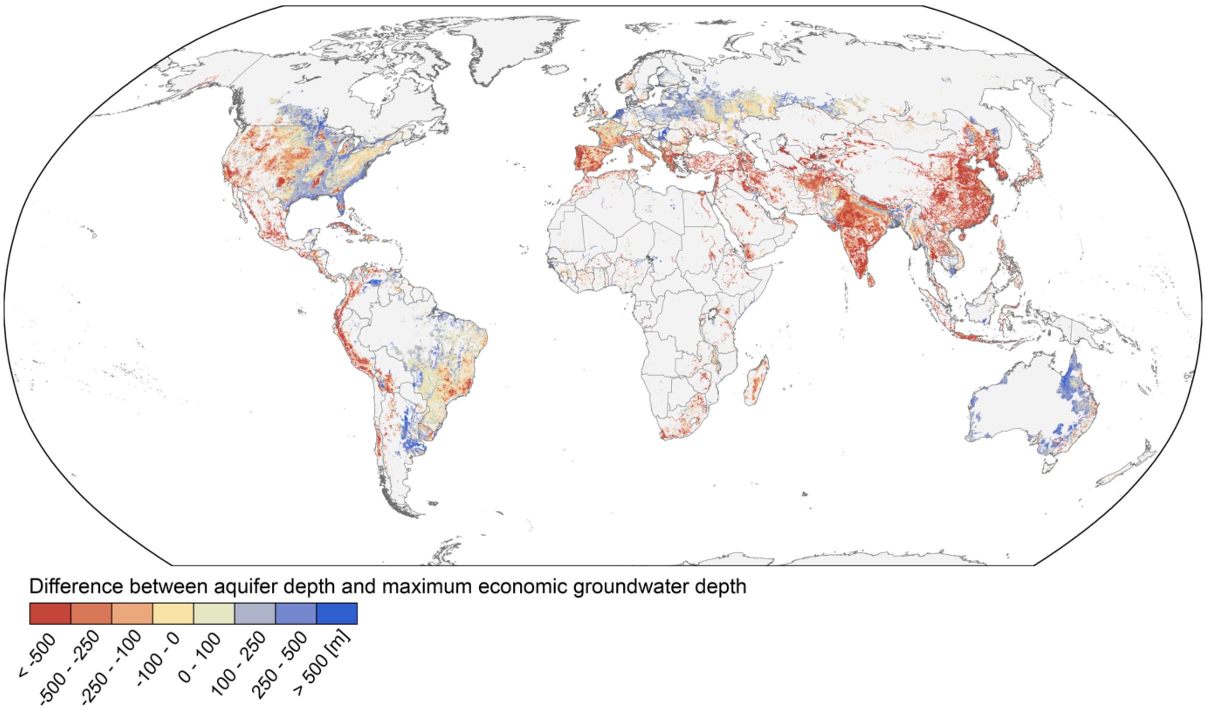
Supplementary Figure 6. Contribution of the dominant variable (Supplementary Figure 5) to the uncertainty in estimated maximum economic groundwater depth (in terms of fraction of variance); cells for which no irrigated agriculture is present are in grey.



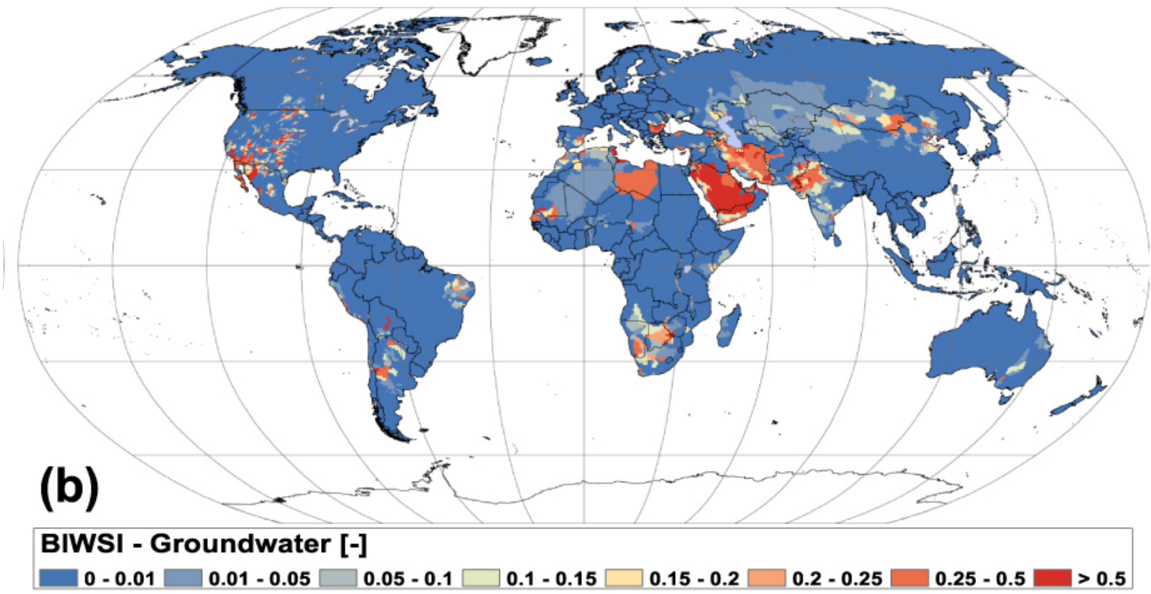
Supplementary Figure 7: Economic depletion over time. Time series of cumulative groundwater withdrawn (1000 km^3) (blue) and net present value of groundwater stocks (billion USD) remaining in the ground (red) under currently irrigated areas. The dashed lines represent uncertainty boundaries (25% and 75% percentiles assuming a log-normal distribution).



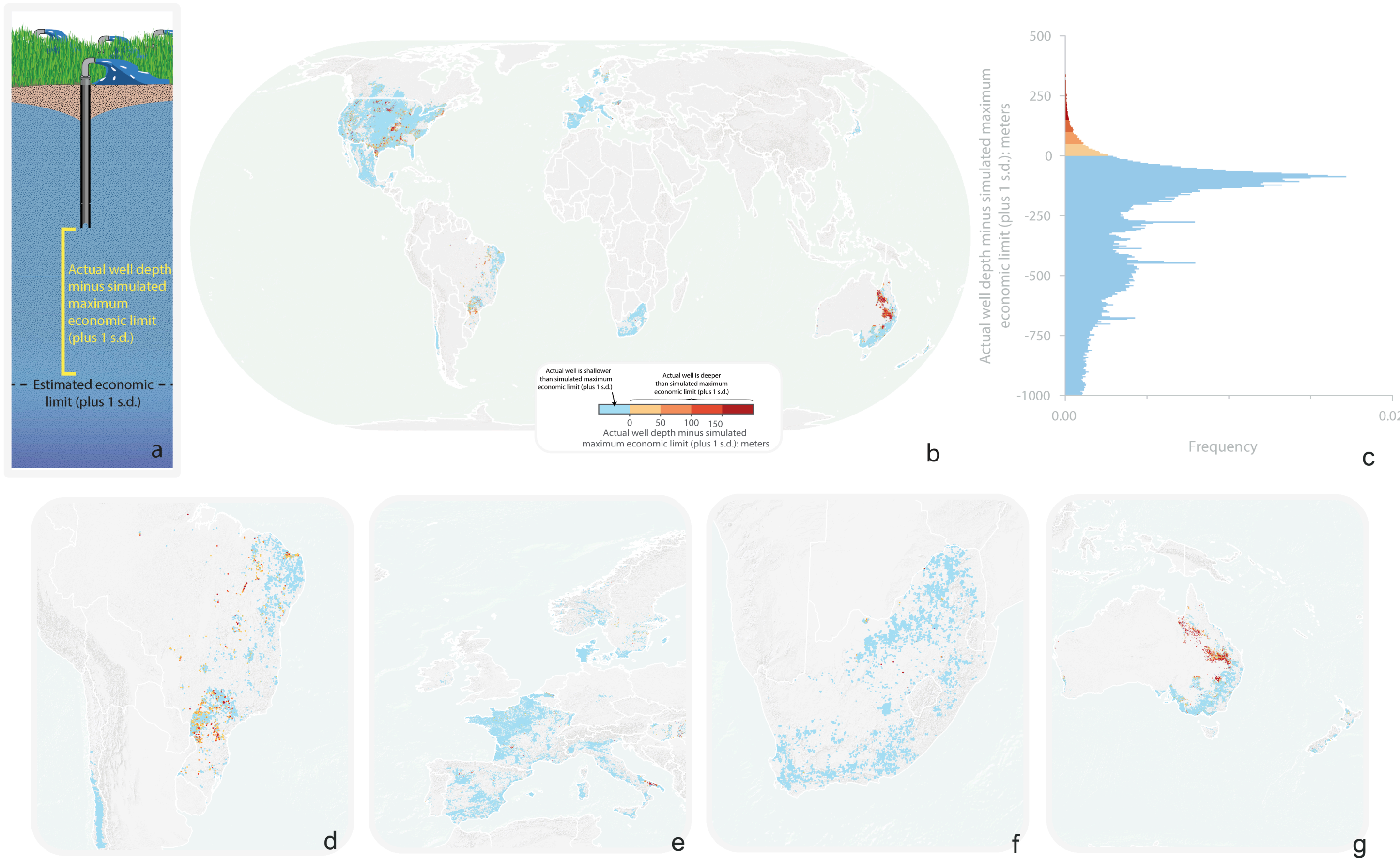
Supplementary Figure 8: Reaching the economic limit for groundwater irrigation as a last resort: (a) fraction of the world's irrigated area that has reached the maximum economic groundwater depth; and, (b) box plots of the maximum economic depth of wells in productive and less productive aquifers; per box plot, the whiskers represent the minimum and maximum well depth, the horizontal line the log-normal mean and the box the boundaries ± 1 log-normal standard deviation and the symbol the arithmetic mean.



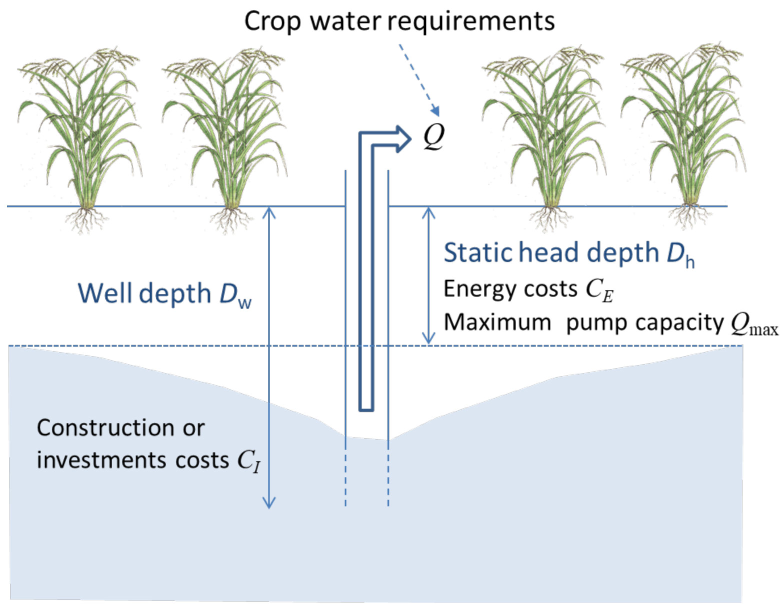
Supplementary Figure 9. Difference between the bottom of the aquifers represented in a global groundwater model[27] (representing the depth to crystalline bedrock including unconsolidated sedimentary deposits and sedimentary rocks) and the maximum economic groundwater depth [m]. Negative values indicate that the maximum economic groundwater depth is larger than the physical aquifer depth; cells for which no irrigated agriculture is present are in grey.



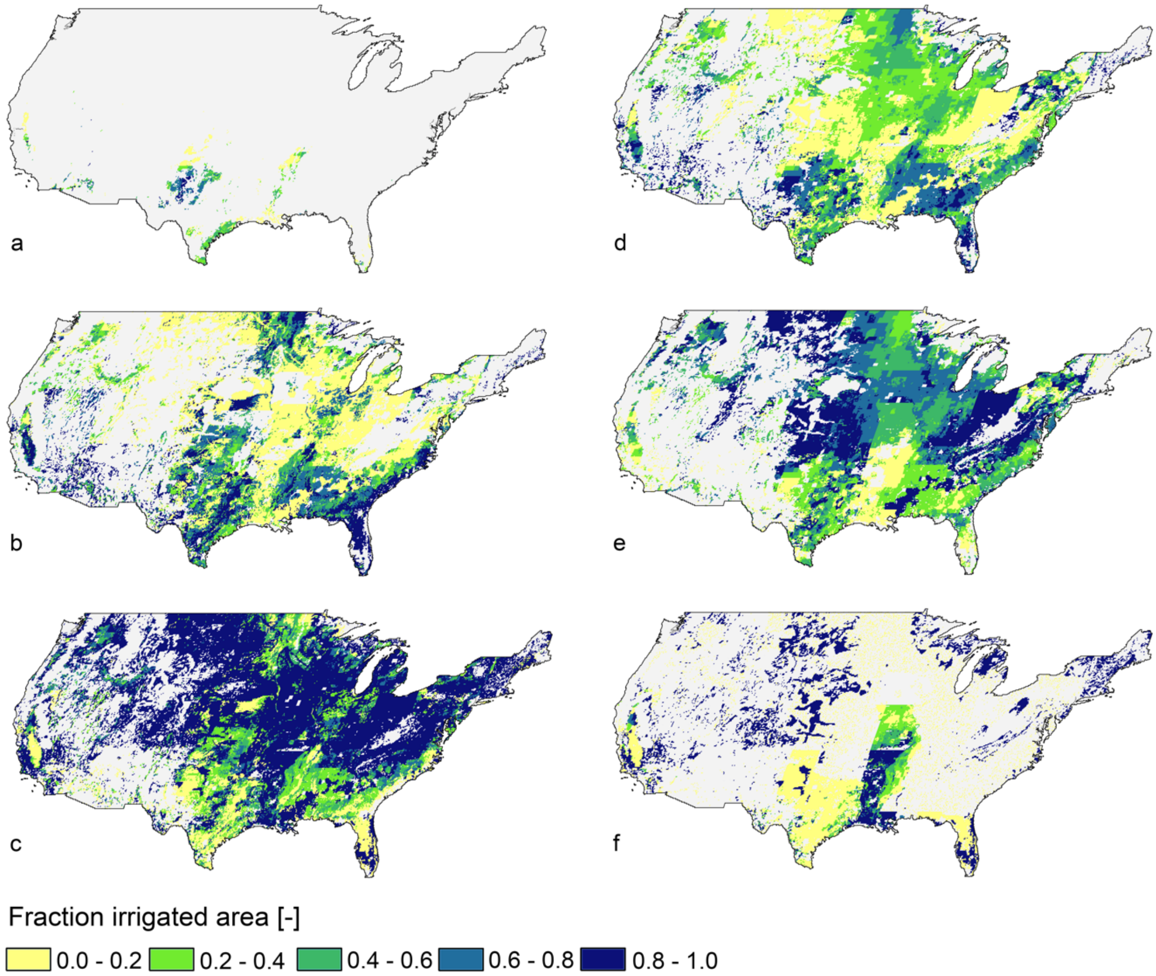
Supplementary Figure 10. Fraction of irrigation water coming from non-renewable groundwater withdrawal, which is equal to the groundwater part of the Blue Water Scarcity Index (BLWSI) according to Wada and Bierkens (2014)[28].



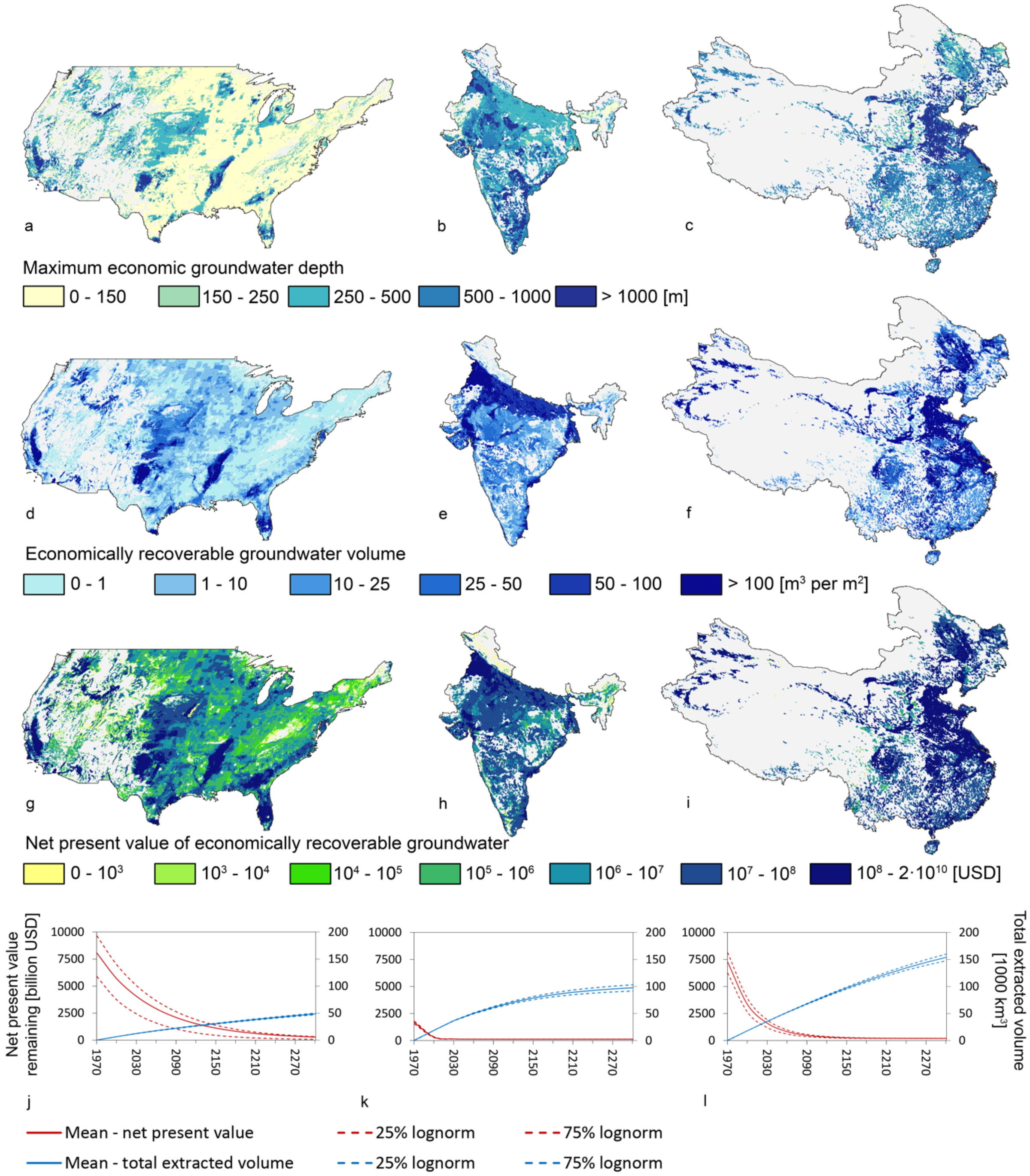
Supplementary Figure 11. Evaluation of maximum economic groundwater depth and associated well depth. (a) schematic showing the difference (in yellow) between the maximum economic well depth (estimate + 1 standard deviation) and the actual well depth. (b) Map of differences between reported well depths[29] and maximum economic well depth (estimate +1 standard deviation) (average per 5 arcminute cell) over CONUS in metres. Positive values mean that reported well depths are larger than maximum economic well depth. (c) Frequency distribution of the difference between reported well depths[29] and the maximum economic well depth. (d-g) Insets of regions of interest: South America, Western Europe, Southern Africa and Australia and Pacific; grey denotes areas without information on groundwater extraction wells.



Supplementary Fig. 12. Schematic representation of groundwater pumping for irrigation, with investment costs C_I depending on the well depth D_w and energy costs to lift the water C_E and the maximum pump capacity Q_{max} depending on the static head depth Dh. The required pumping rate Q is assumed equal to the crop water demands.



Supplementary Figure 23. Fractional contribution per cell of the irrigation type for the contiguous USA (CONUS). Left-hand side panels (a, b and c) show the current distribution for the types drip, sprinkler and surface (a, b and c respectively), as taken from Supplementary Methods Fig. 1. Right-hand side panels (d, e and f) show the same irrigation types (drip, sprinkler and surface) but now with the type that is the most efficient in terms of irrigation water use to the relevant crops (see Methods and Supplementary Methods Table 4). Cells for which an irrigation type is absent, i.e., the fraction is zero, are shown in grey.



Supplementary Figure 14. Details for the selected regions (contiguous USA (CONUS), India and China) for the maximum economic groundwater depth, identical to Fig. 1 (panels a-c), for the equivalent depth of the extracted groundwater volume, identical to Fig. 2 (panels d-f), for the net present value, identical to Fig. 3 (panels g-i), and of the timeseries of their respective totals over these regions, identical to Supplementary Fig. 7 (panels j-l).

Supplementary Tables

Supplementary Table 1. *Volume (km^3) and NPV (million USD) of economically recoverable groundwater of currently irrigated areas of the top seven groundwater depleting countries. For reference, we also show the actual groundwater withdrawal and depletion rates (km^3.year^{-1} for 2010) estimated by Wada and Bierkens[28] and the current gross revenues from agricultural production for these countries[30].*

Country	Ground-water withdrawal[28] (2010; km^3.year^{-1})	Ground-water depletion[28] (2010; km^3.year^{-1})	Volume of economically recoverable groundwater (km^3)	NPV of economically recoverable groundwater under currently irrigated areas (million USD)	Total income from irrigation (million USD.year^{-1})	Current gross value of agricultural production[30] (2010) (million USD.year^{-1})
India	250	80	$1.10 \cdot 10^5$	$1.54 \cdot 10^6$	$1.39 \cdot 10^5$	$3.58 \cdot 10^5$
USA	125	23	$9.72 \cdot 10^4$	$7.96 \cdot 10^6$	$1.06 \cdot 10^5$	$4.41 \cdot 10^5$
China	110	28	$2.28 \cdot 10^5$	$7.05 \cdot 10^6$	$2.21 \cdot 10^5$	$1.13 \cdot 10^6$
Pakistan	80	46	$3.02 \cdot 10^4$	$6.40 \cdot 10^5$	$4.22 \cdot 10^4$	$4.67 \cdot 10^4$
Iran	72	47	$3.79 \cdot 10^4$	$2.29 \cdot 10^5$	$3.38 \cdot 10^4$	$5.31 \cdot 10^4$
Mexico	42	10	$2.74 \cdot 10^4$	$1.33 \cdot 10^6$	$2.01 \cdot 10^4$	$5.69 \cdot 10^4$
Saudi Arabia	25	20	$9.07 \cdot 10^3$	$6.27 \cdot 10^4$	$1.54 \cdot 10^4$	$1.49 \cdot 10^4$
Globe	952	304	$8.82 \cdot 10^5$	$2.81 \cdot 10^7$	$1.01 \cdot 10^6$	$4.27 \cdot 10^6$

Supplementary Table 2. *Changes in maximum economic groundwater depth (m), and volume (km^3) and net present value (NPV; million USD) of economically recoverable groundwater for CONUS following the use of more profitable crops and/or improved irrigation efficiency. Values in brackets are the relative changes compared to the standard scenario in our simulation (*Actual irrigation efficiency, current crops*).*

	Actual irrigation efficiency, current crops	Actual irrigation efficiency, more profitable crops	Relative changes compared to actual irrigation efficiency and current crops	Improved irrigation effici-ency and current crops	relative changes compared to actual irrigation efficiency and current crops	Improved irrigation efficiency and more profitable crops	relative changes compared to actual irrigation efficiency and current crops
Maximum economic groundwater depth (m)							
Max	3759.2	3859.1	(3%)	4909.1	(31%)	4927.5	(31%)
Mean	268.2	298.1	(11%)	262.1	(-2%)	286.7	(7%)
standard deviation	301.3	400.4	(33%)	300.2	(0%)	394.2	(31%)
Net present value (million USD)	$7.82\ 10^6$	$14.12\ 10^6$	(81%)	$8.16\ 10^6$	(4%)	$14.6\ 10^6$	(86%)
Volume economically recoverable groundwater (1000 km^3)	95.8	117.4	(23%)	90.4	(-6%)	107.7	(12%)
Net revenue per unit groundwater (USD/m^3)	0.082	0.120	(47%)	0.090	(10%)	0.135	(66%)

***Supplementary Table 3**. Parameters used in the model to estimate maximum economic groundwater depth; All parameters are fixed in time (based upon a representative, average year). Parameter, description, mean values and range, as well as the standard deviation (in brackets) representing assumed uncertainty and references to sources.*

Parameter	**Description**	**Unit**	**Resolution**	**Value (range for distributed values)**	**Uncertainty**	**Reference**
Groundwater						
D_h	Groundwater depth (initial value)	[m]	5'	110 (0 – 3270)	-	De Graaf et al. (2017)[27]
D_c	Thickness of the confining layer	[m]	5'	14.6 (0 – 150)	mul. (f^-: 0.90, f^+: 1.10)	
N	Specific yield	[m³/m³]	5'	0.103 (0.001 – 0.358)	mul. (f^-: 0.166 – 0.878, f^+: 1.14 – 6.00)	Gleeson et al. (2014)[26]
Sy	Storativity confined aquifer	[m/m]	Uniform	0.001	5' (x^-: $1.32\cdot10^{-4}$ – $6.81\cdot10^{-4}$ x^+: $1.47\cdot10^{-3}$ – $7.55\cdot10^{-3}$)	This study
Irrigation						
A_i	Crop area per crop	[ha]	5', for all irrigated crops	-		Portmann et al. (2002)[2]
Q_i	Irrigation water requirement per crop	[m3/m2/year]	5', for all irrigated crops			Allen et al. (1998)[3]
f_{irr}	Irrigation type	[-]	5', per irrigation type	Surface, sprinkler, drip		This study
e_{irr}	Irrigation efficiency	[-]	Uniform, per irrigation type	0.50, 0.75, 0.90		Brouwer et al. (1989)[6]
Well + infrastructure construction						
C_{p_a}	Offset pump cost	USD / pump	Country	30 000*	mul. (f^-: 0.750, f^+: 1.25)	This study
C_{p_b}	Rate pump cost	USD / kW	Country	150*	mul. (f^-: 0.750, f^+: 1.25)	This study
C_{irr}	Irrigation cost	USD / ha	Country, per irrigation typ	568, 1165, 2795*	mul. (f-: *0.750*, f^+: 1.25)	This study
C_M	Material cost	USD /m	Country	967*	mul. (f-: *0.750*, f^+: 1.25)	This study

C_L	Labour cost	USD /m	Country	300*	mul. (f^-: 0.800, f^+: 1.20)	This study
P_{kWH}	Electricity price	USD /kWH	Country	0.07 (0.05 – 0.22)	mul. (f^-: 0.870, f^+: 1.13)	OECD[18], Eurostat[22]
D_f	Filter depth	[m]	Uniform	60	-	PSU [n.d.]
Q_{max}	Pump capacity**	[m^3/year]	Uniform	770,921	-	
Pumping efficiency						
ϵ_i	Initial pumping efficiency	[-]	Uniform	0.950	add. (Δx^-: -0.100, Δx^+: + 0.025)	This study
ϵ_f	Final pumping efficency	[-]	Uniform	0.600	add. (Δx^-: -0.100, Δx^+: + 0.025	This study
z_{ref}	Reference depth	[m]	Uniform	180	-	This study
Socio-economic information						
WP	Water productivity	[$kg \cdot m^{-3}$]	Uniform per crop	0.55 – 14		FAO[30]
P_i	Crop price	USD / tonne	Country, per crop	34 – 34 000 (2.90 – 94 000)	mul. (f^-: 0.952, f^+: 1.05)	FAO[30]
R	Discount rate	[%]	Country	1 (1 – 51.5)	add. (Δx^-: -0.50, Δx^+: + 3.0	World Bank[25]
i_ℓ	Interest rate	[%]	Country	3 (3 – 53.5)	add. (Δx^-: -0.50, Δx^+: + 3.0	World Bank[25]

*: for the country data, values vary relative to the estimates of the USA between $4.96 \cdot 10^{-3}$ and 3.26 [-].
**: This is the pump capacity which is not affected by the pumping efficiency

Supplementary Table 4. *Irrigated areas per crop over the contiguous USA (CONUS) for the current crop distribution*[2] *(see also Supplementary Methods: Table 1 for crops and numbering) and for the most profitable crops in each cell. The most profitable crops were identified on the basis of the currently irrigated crops in a cell in terms of the net revenue they return, i.e., revenue minus costs, per unit of groundwater over the first investment period (see Methods). The rank number in the table identifies the five regionally most profitable crops but less profitable crops may still be present in a cell as a result of the actual crops presence, their revenue and the incurred costs over the investment period considered. The change shows the shift in cultivated areas over CONUS per crop*

ID	Crop name	Net revenue per unit economically recoverable groundwater	Rank	Irrigated area per crop		Change
				Current crop	In case of most profitable crop per grid cell	
-	-	[USD/m^3]	-	[km^2]	[km^2]	[%]
1	Wheat	0.095		12036.3	4515.6	-62.5
2	Maize	0.148		48130.4	42340.6	-12.0
3	Rice	0.119		12943.4	7540.1	-41.7
4	Barley	0.128		3599.9	1995.8	-44.6
5	Rye	0.136		175.4	34.0	-80.6
6	Millet	0.042		37.7	3.5	-90.7
7	Sorghum	0.076		3467.1	724.9	-79.1
8	Soybeans	0.122		21788.5	15723.9	-27.8
9	Sunflower	0.134		273.2	133.0	-51.3
10	Potatoes	1.446	2	4164.0	11940.0	186.7
12	Sugar cane	0.184		1801.9	973.3	-46.0
13	Sugar beets	0.263		1882.7	1900.9	1.0
15	Rapeseed / Canola	0.492	5	33.0	66.0	99.9
16	Groundnuts / Peanuts	0.280		1863.1	881.3	-52.7
17	Pulses	0.174		2373.5	2090.8	-11.9
18	Citrus	0.941	4	4864.0	5889.0	21.1
19	Grapes and vine	1.307	3	3743.8	6124.0	63.6
20	Cotton	1.465	1	19541.1	39842.2	103.9

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