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Water Resources Research

RESEARCH ARTICLE

10.1029/2021WR031924

Technical and Economic Irrigation Potentials Within Land and Water Boundaries

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Key Points:

- Our data processing routine provides a hydrological input aggregation tool to global land-system models
- We find considerable global potential to expand irrigation within local environmental (land and water) limits
- Of the 2,144 Mha that could technically be irrigated, only 698 (330) Mha have a yield gain of at least 300 (600) USD ha^{-1}

Supporting Information:

Supporting Information may be found in the online version of this article.

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Citation:

Beier, F. D., Bodirsky, B. L., Heinke, J., Karstens, K., Dietrich, J. P., Müller, C., et al. (2023). Technical and economic irrigation potentials within land and water boundaries. *Water Resources Research*, *59*, e2021WR031924. https://doi.org/10.1029/2021WR031924

Received 31 DEC 2021
Accepted 16 MAR 2023

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Abstract

To satisfy the increasing global demand for agricultural products, the expansion of irrigation is an important intensification measure. At the same time, unsustainable water abstractions and cropland expansion pose a threat to biodiversity and ecosystem functioning. Irrigation potentials are influenced by local biophysical irrigation water availability and competition of different water users. Using a novel hydro-economic data processing routine that considers economic criteria of water allocation via a productivity ranking of grid cells and both land and water sustainability criteria, we estimate global irrigation potentials at a 0.5° spatial resolution. We show that there is considerable technical potential to expand irrigation within local water and land boundaries. In terms of potentially irrigated areas on all global land suitable for crop production, 2,144 Mha could be irrigated within land and water environmental boundaries when only considering biophysical criteria. However, not all of these areas would actually be irrigated under consideration of irrigation costs. Of these, only 698 Mha (330 Mha) have a yield gain of more than 300 (600) USD ha^{-1} under the current crop mix valued at their current commodity price (economic irrigation potential).

Plain Language Summary

Irrigation plays an important role in food production. Global crop demand is expected to increase due to the growing world population and increasing role of bioenergy to mitigate climate change. Irrigation can contribute to meeting this increasing demand by facilitating higher crop yields per hectare of agricultural land, but also has environmental consequences. In this study, we quantify the areas across the globe that can be irrigated given economic and environmental constraints. We determine how much area and which areas can be irrigated globally given local water availability; how much of these can be irrigated while protecting water flows and land for biodiversity conservation; as well as the economic benefit of irrigation in different locations. We find that 2,144 Mha could be irrigated globally while respecting land and water environmental boundaries when only considering biophysical constraints. In reality, many of these areas might not be irrigated for economic reasons. Where the gain through irrigation is small, farmers might not install irrigation equipment. According to our estimation, only 698 Mha (362 Mha) have yield gains of at least 300 (600) USD ha^{-1}.

1. Introduction

Irrigation plays an important role in global food production (Foley et al., 2011; Ringler & Zhu, 2015), and the expansion of irrigation is an important intensification measure to satisfy the increasing global demand for agricultural outputs (Keating et al., 2014). Further global population growth (United Nations, 2019) drives increases in absolute food demand (Bodirsky et al., 2020). At the same time, food demand in developing and emerging economies is expected to grow and shift to an increasingly land- and water-intensive diet (Bodirsky et al., 2020; Ringler & Zhu, 2015; Tilman & Clark, 2014). Additionally, with the increasing role of bioenergy crop production for climate change mitigation, competition for land and water resources between the food and bioenergy sector is rising (Bonsch et al., 2016; Klein et al., 2014; Stenzel et al., 2021). Irrigation can contribute to closing the yield gap by generating higher agricultural outputs per hectare (Foley et al., 2011; Mueller et al., 2012; Rosa et al., 2018). However, already today, irrigation relies in many parts of the world on unsustainable withdrawals (Wada & Bierkens, 2014) and taps environmental flows necessary to maintain functioning aquatic and riverine ecosystems (Jägermeyr et al., 2017).

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A defining question of our time is how human demands may evolve in the future and how they can be satisfied within environmental and economic limits (Rockström et al., 2009; Rosa et al., 2018; Soergel et al., 2021). To this end, a global quantification of economic irrigation potentials considering local land and water constraints in terms of potential irrigation water use (explicitly distinguishing withdrawals and consumption) as well as potentially irrigated areas (PIA) is necessary. Previous approaches quantifying irrigation potentials and sustainable irrigation water use considering upstream-downstream effects focused solely on current cropland and irrigation expansion into currently rainfed areas (Jenkins et al., 2021; Rosa, Chiarelli, Rulli, et al., 2020; Rosa et al., 2018). Furthermore, they allocate water to upstream users first (D'Odorico et al., 2020; Rosa et al., 2018; Rosa, Chiarelli, Sangiorgio, et al., 2020), and thereby disregard that the economic irrigation potential may be higher if water was spared for downstream users with higher water productivity. With respect to environmental conservation, previous approaches focused on environmental flow protection only (Jägermeyr et al., 2017; Mekonnen & Hoekstra, 2020; Rosa, Chiarelli, Sangiorgio, et al., 2020), not considering land conservation.

We add to the literature by providing global spatially explicit irrigation potentials in terms of potential irrigation water as well as PIA under economic decision making criteria. That is, the irrigation water withdrawal location is determined by the relative water productivity. Our contribution is threefold: First, rather than allocating water based on an upstream-first rule, it is allocated based on its most productive usage that may also be further downstream. Second, we determine the potential of irrigation expansion, not only into rainfed cultivated land, but also into uncultivated land that is suitable for crop production. Third, because of the threats that cropland expansion and intensification pose on biodiversity and species loss through habitat loss and landscape simplification (IPBES, 2019; Matson et al., 1997; Zabel et al., 2019), we take two sustainability dimensions (land protection and water flow protection) into account. Providing estimates of irrigation area expansion potential on all suitable land under consideration of environmental and economic constraints is crucial for global Land System Models (LSMs). Only by including potential cropland in the determination of irrigation potentials, these models have the full option space for cropland and irrigation expansion and can assess how much area to put into production effectively, while taking further criteria such as food demand, greenhouse gas policies and sustainability trade-offs into account. With the estimation of Potential Irrigation Water Consumption (PIWC), our research also adds to the literature on a potential "planetary water opportunities" boundary (Gerten et al., 2013; Jenkins et al., 2021; Rockström et al., 2009). To estimate this boundary, assessing societal water demands and areas where the water would actually be used is important (Gerten et al., 2013). Our assessment of irrigation potentials excludes areas that are not suitable for cropping activities and considers potential human water demands.

Our global open-source spatially explicit (0.5° resolution) hydro-economic data processing routine allocates irrigation water abstractions based on a productivity ranking. Moreover, it considers competition by upstream water consumption and downstream water withdrawals when determining local water availability, considering also other (human and environmental) water usage. It takes both biophysical conditions as well as economic criteria into account to derive irrigation potentials (i.e., PIWC; potential irrigation water withdrawal (PIWW); PIA) at grid cell level. The latter can be used to derive marginal PIA curves showing the PIA ranked by their monetarized yield gain. These marginal irrigation yield gain curves depict the maximum area that can potentially be irrigated at different yield gains for aggregated units (e.g., river basins or national territories). We limit our analysis to irrigation potentials for a single cropping season using only surface water and renewable groundwater resources without considering deficit irrigation. Our approach relies on water balance calculations over long time scales aiming to represent the global spatial long-term irrigation potential.

With this model, we address the following research questions: How much area can be irrigated on current cropland and on potential cropland? How would the technical and economic irrigation potentials be reduced under water and land conservation? And finally, where do high yield gains from irrigation coincide with high water scarcity, elevating the risk of unsustainable withdrawals?

2. Methodology

Our method aims at providing long-term technical and economic irrigation potentials on current and potential cropland. The objective is to provide a global spatial water balance taking different users and their upstream-downstream effects as well as relative water productivity into account. The approach relies on an unequivocal relationship between water use in one cell and reduced water availability in downstream cells. To achieve this within a model of limited complexity, the approach is based on long-term water budgets. These are

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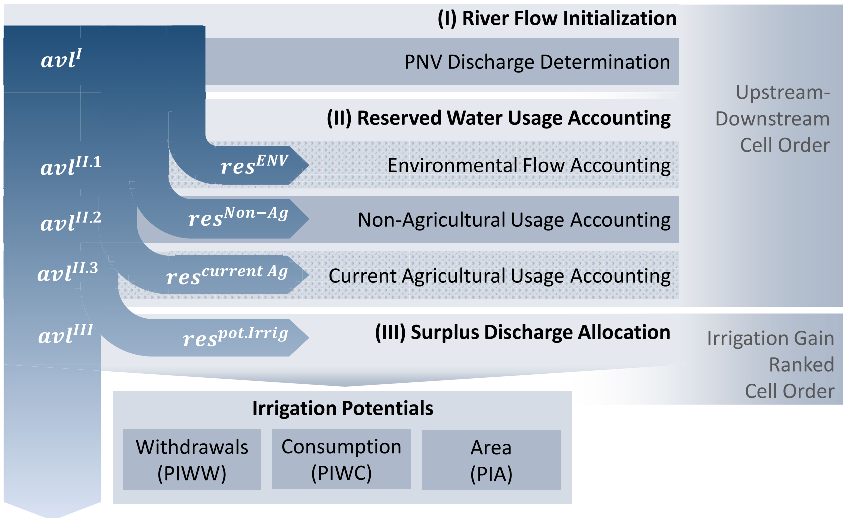

Figure 1. Sequence of flow accumulation steps of the hydro-economic routine determining potential irrigation water withdrawal (PIWW) and consumption (PIWC) and potentially irrigated area (PIA). avl^{i} refers to the available water after the respective flow determination step; res^{i} refers to the water volume reserved in the respective step. Scenario-dependent optional flow determination steps (Environmental Flow Accounting and Current Agricultural Usage Accounting) are indicated as lightly dotted boxes.

obtained by smoothing all biophysical input data from 1965 to 2017 via a cubic spline with 4° of freedom per 100 years (Chambers & Hastie, 1992; Ripley & Maechler, 2021). To obtain a robust long-term value, data before and after the year of interest is required. For that reason, we have chosen 2010 as year to be represented.

To account for the upstream-downstream effects of water abstractions along the river, we developed a hydro-economic data processing routine for water flows and water abstractions consisting of a sequence of flow accumulation algorithms. This routine determines in an iterative process the discharge (and thus available water for irrigation) for each grid cell based on accumulated upstream water availability, allocated environmental flows, and human water usage (spatial water balance). This spatial water balance approach is similar to the method employed for the estimation of global irrigated biomass production potentials by Jans et al. (2018).

All hydrological inputs (runoff, discharge, evaporation from water bodies) as well as yields and crop water requirements are provided by the Lund–Potsdam–Jena dynamic global vegetation model with managed Land (LPJmL) (Schaphoff, von Bloh et al., 2018; von Bloh et al., 2018). For a detailed LPJmL model description including specific modeling assumptions, see Supporting Information S1.

Figure 1 provides a graphical representation of the consecutive flow determination steps and outputs of the hydro-economic data processing routine. The first flow determination step initializes river discharge (see (I) in Figure 1) based on "potential natural vegetation (PNV) discharge" (q^{PNV}, see Equation 1).

$$
\begin{aligned}
q_c^{PNV} &= in_c + r_c - e_c \\
in_c &= \sum_{up} q_{up}^{PNV}
\end{aligned}
\tag{1}
$$

in_c is the inflow into cell c from its direct upstream neighbor cells up; r_c is runoff on cell c; and e_c lake evaporation in cell c. PNV discharge refers to discharge under potential natural vegatation ignoring the influence of anthropogenic effects on discharge. To this end, we use runoff and lake evaporation provided by a simulation of runoff with LPJmL4 (Schaphoff, von Bloh et al., 2018) for a hypothetical 100% PNV only setup with current climate forcing data from the Global Soil Wetness Project Phase 3 (GSWP3-W5E5) data set (Cucchi et al., 2020; Kim, 2017; Lange et al., 2021, 2022).

2.1. River Flow Constraints

In the cell water balance of the subsequent flow determination steps (see (II) and (III) in Figure 1), previously "reserved flows" (res_c) are accounted for and affect water availability for usage in the next flow determination

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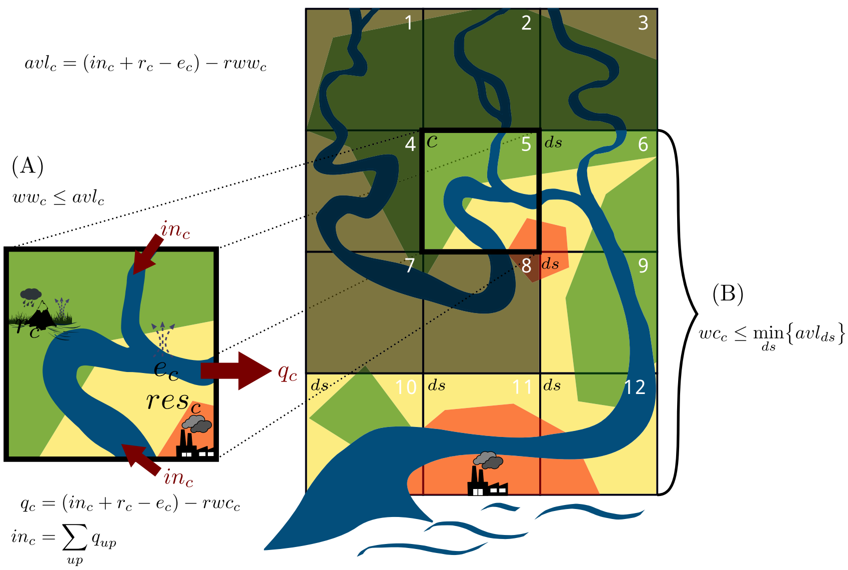

Figure 2. Illustration of water use constraints emerging from upstream-downstream relationships within the river network at the example of the iteration step of cell $c = 5$. According to the local withdrawal constraint (A), water withdrawals in cell c (ww_c) must not violate local availability (avl_c). According to the downstream consumption constraint (B), water consumption in cell c (wc_c) must not violate downstream availability (avl_{ds}) where $ds = \{6, 9, 12, 11, 10\}$ are the respective downstream cells of $c = 5$. Availability is determined by inflows from upstream cells (*in*), runoff (*r*), lake and river evaporation (*e*) and reserved withdrawals (*rww*). The latter capture environmental flows; non-agricultural withdrawals; and/or current agricultural withdrawals, depending on the stage of the allocation process. Available water that is not consumed in cell c flows as discharge (q_c) into the adjacent downstream cell and by that updating avl_c for all downstream cells before the next cell is being calculated.

step. We distinguish reserved consumption (*rwc*) and reserved withdrawals (*rww*). Locally available renewable water (avl_c) is calculated from local runoff (r_c), local lake and river evaporation (e_c) and upstream inflows into cell c (in_c). Inflows in turn are determined by the discharge from their direct upstream cells (*up*). Additionally, in calculation steps with previously considered other uses (environment; non-agriculture; current agriculture), the respectively reserved withdrawals (rww_c) in each cell c are subtracted from the available water in that cell (see Equation 2).

$$avl_c = (in_c + r_c - e_c) - rww_c \tag{2}$$

Discharge from cell c to the adjacent grid cell (q_c) accounts for reserved water consumption (rwc_c) (see Equation 3).

$$\begin{aligned} q_c &= (in_c + r_c - e_c) - rwc_c \\ in_c &= \sum_{up} q_{up} \end{aligned} \tag{3}$$

In every iteration step, two constraints of local grid cell specific and downstream discharge must be fulfilled (see Figure 2): the "withdrawal constraint" (A) and the "consumption constraint" (B). As soon as water is reserved, discharge is updated according to Equation 3 for its downstream cells. Note that this implies that return flows ($rww - rwc$) cannot be re-used locally in the same grid cell, but are available downstream (see Equation 3).

(A) **Withdrawal constraint**: Local withdrawals (ww_c) in each grid cell are constrained by local availability, avl_c (Equation 4).

$$ww_c \leq avl_c \tag{4}$$

(B) **Consumption constraint**: Local consumption (wc_c) is additionally constrained by providing sufficient water to previously reserved downstream withdrawals (Equation 5). More concretely, water that is reserved to be withdrawn in a downstream cell (*ds*) of cell c for a priority use, that cannot be fulfilled by local runoff in that particular downstream cell, needs to come from inflows into this cell. Therefore, it cannot be consumed in the respective upstream cell(s) in the current flow routing.

$$wc_c \leq \min_{ds} \{avl_{ds}\} \tag{5}$$

ds represents the set of downstream cells to cell c.

2.2. Reserved Water Use Accounting

To account for water uses that have priority over irrigation in our model, the (partly optional) flow determination algorithms are executed sequentially as part of the Reserved Water Use Accounting (see (II) in Figure 1). Through the order of execution of flow determination algorithms, environmental flows (for protection scenarios only) are prioritized over human uses; and non-agricultural human uses over agricultural water use.

Environmental flow requirements (EFR)—that is, the minimum flow to maintain the aquatic and riverine ecosystem in a "fair condition" (Smakhtin et al., 2004)—are (optionally) reserved to prevent unsustainable human water abstractions (only in the respective protection scenarios (see Section 2.5)). EFR are calculated using the variable monthly flow (VMF) method (Pastor et al., 2014). Because our algorithm operates with long-term annual averages, but the calculation of EFR requires information on timing and variability of discharge, we need monthly discharge to derive the flow that needs to be withhold for the environment. We use monthly PNV discharge calculated by the temporally highly resolved river routing routine of LPJmL4 (Schaphoff, von Bloh et al., 2018). For the full EFR methodology applied in this study, see Supporting Information S1.

In terms of human water use, we differentiate water withdrawal and water consumption (see Section 2.1 for a detailed description of the withdrawal and consumption constraints). Water consumption refers to the total water volume taken up by the production process through evaporation, transpiration or incorporation into the product or plant. Withdrawal refers to the water volume diverted from water bodies (Flörke et al., 2013; Jägermeyr et al., 2015). Withdrawals that are not consumed are returned to the river (return flow) (Jägermeyr et al., 2015).

Non-agricultural water use is prioritized over agricultural use (see Figure 1) because domestic and industrial water uses usually have a higher marginal return compared to agricultural water use (D'Odorico et al., 2020; United Nations, 2021). Similar assumptions are also made in several global economic optimization models (Baldos et al., 2020; Bonsch et al., 2016; Pastor et al., 2019; Robinson et al., 2015). Non-agricultural annual water withdrawals and consumption for domestic and industrial uses are a multi-model average provided by the Water Futures and Solutions project (Wada et al., 2016) as part of the Inter-Sectoral Impact Model Intercomparison Project (version ISIMIP3b (2020)). Because of a lack of spatially explicit data, we do not include direct water consumption by livestock. With around 1%–2% of total global water use, it is negligible (United Nations, 2021).

For the optional scenario setting of reserved current agricultural water usage, current grid cell specific irrigation water withdrawals and consumption are calculated based on blue water consumption requirements of crops as provided by LPJmL5 (Lutz et al., 2019; von Bloh et al., 2018) and the current grid cell specific crop mix as well as currently irrigated areas. Grid cell and crop-specific irrigated areas are derived from national crop harvesting data from FAOSTAT (FAO, 2021) and grid cell specific irrigated and rainfed cropland area shares from the LUH2 land use data set that provides the spatial distribution of five crop types (Hurtt et al., 2020) using the crop mapping provided in Supporting Information S2. Water withdrawals further depend on the system specific irrigation efficiency. We take country-specific irrigation system shares for surface, sprinkler and drip irrigation and the respective crop suitability per irrigation system provided by Jägermeyr et al. (2015) to determine crop- and location-specific irrigation efficiencies. Conveyance efficiency (i.e., the percentage of irrigation water diverted from water bodies that reaches the field, Jägermeyr et al., 2015) is assumed to be 70% for open canals (surface), and 95% for pipes (sprinkler and drip) following Schaphoff, von Bloh et al. (2018) and Jägermeyr et al. (2015). Field efficiencies (i.e., the percentage of irrigation water applied to the field i.e., consumed (Jägermeyr et al., 2015) of 52% (surface), 78% (sprinkler) and 88% (drip) are taken from Jägermeyr et al. (2015). For further details see Supporting Information S1.

2.3. Surplus Water Allocation Algorithm

After having accounted for the prioritized water uses following an upstream-to-downstream cell ordering, the remaining water ("surplus water" (see $avl_{II.3}$ in Figure 1)) can potentially be used for additional irrigation in the respective grid cells that have sufficient available water.

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2.3.1. Economic Criteria for Discharge Allocation

The irrigation withdrawal location is determined based on a ranked cell ordering. Grid cells are ordered according to their water productivity gain (Δy_c, in USD m^{-3}) determined as displayed in Equation 6.

$$\Delta y_c = \frac{\Delta z_c}{\sum_k s_{c,k} \cdot w_{c,k}} \tag{6}$$

Δz_c is the potential aggregate yield gain through irrigation (in USD ha^{-1}) in cell c; $s_{c,k}$ is the share of the area of crop k in the total cropland area of cell c; and $w_{c,k}$ are water requirements in terms of required water withdrawals per crop k in cell c. The potential yield gain through irrigation (Δz_c) is calculated as displayed in Equation 7.

$$\Delta z_c = \sum_k \max\left(s_{c,k} \cdot \left(y_{c,k}^{ir} - y_{c,k}^{rf}\right) \cdot p_k, 0\right) \tag{7}$$

$y_{c,k}^{ir}$ $\left(y_{c,k}^{rf}\right)$ are irrigated (rainfed) yields of crop k in cell c (in tons of dry matter (tDM) per hectare); and p_k is the global average price of crop k (in USD tDM^{-1}). We use the current crop mix of the year 2010 and globally averaged agricultural commodity prices reported by FAO (2021) to compare yield gains between cells with different cultivated crop species. We choose global commodity prices instead of regional prices because we aim to compare yield gains and water productivity across different administrative borders (e.g., our water allocation algorithm should not assign more water to a country that has import tariffs and therefore higher prices). Crop commodity prices are averaged over the period 2008 to 2010 to balance price fluctuations.

Spatially explicit irrigated and rainfed crop yields are provided by LPJmL5 (Lutz et al., 2019; von Bloh et al., 2018). Negative yield gains $\left(y_{c,k}^{ir} < y_{c,k}^{rf}\right)$ are technically possible because irrigation may lead to a shift in the growing period in LPJmL resulting in lower irrigated yields. In such cases, the irrigation yield gain of the respective crop is set to 0. To be consistent with FAOSTAT production (FAO, 2021), we calibrate LPJmL yields to meet FAO country yields by using a multiplicative factor. The calibration accounts for country-specific management effects on yields, such as fertilizer and pesticide use, different crop varieties and mechanization as well as cropping intensity. For a detailed description of the LPJmL versions used as well as for the yield calibration, see Supporting Information S1.

Based on Δy_c all cells within each river basin are ranked. Provided that a grid cell exceeds a chosen minimum irrigation gain threshold Δz_c, irrigation water is allocated first in the highest ranked cell, reserving the required water for irrigation and updating discharge to the adjacent cell. This procedure is repeated for the next highest ranked cell up to the lowest ranked cell. The irrigation water requirements are determined by the water volume necessary to irrigate the available area under a given crop mix assumption (full irrigation requirements).

With a threshold of 0 USD ha^{-1}, the technically possible maximum irrigation potential can be determined under consideration of optimized local irrigation water availability (technical irrigation potential). Higher thresholds serve to identify areas that are more beneficial than others. To represent "economic irrigation potentials" (i.e., the irrigation potential that can be achieved at a minimum yield gain) under a range of plausible costs, we use a set of different thresholds. In the absence of subsidies, the equipment of area for irrigation should only take place in locations where positive profits from irrigation can be achieved (i.e., additional yield gain from irrigation > additional costs associated with irrigation) (Esteve et al., 2015). Both fixed and variable irrigation costs vary depending on the type of investment (irrigation expansion, irrigation system upgrade, replacement of depreciated capital (Palazzo et al., 2019)), the irrigation project type (small-scale vs. large-scale infrastructure investment (You et al., 2011)) and the geographical location (Inocencio et al., 2007; Jones, 1995). For further information on the annualized regional average costs for irrigation infrastructure investments and on-farm irrigation costs (e.g., additional labor, on-farm irrigation equipment, pumping costs) reported in the literature (Inocencio et al., 2007; You et al., 2011) please refer to the Supporting Information S1. To represent a range of plausible costs, we choose a medium yield gain threshold (300 USD ha^{-1}) and an upper threshold (600 USD ha^{-1}). Based on a range of thresholds between 0 and 1,500 USD ha^{-1} and the resulting irrigation potentials, we derive PIA curves that depict the maximum area that can potentially be irrigated at different yield gains.

2.3.2. Effect of Flow Variability on Water Availability

Water availability does not only depend on the total annual flow availability, but also on its variability throughout the year. Since our approach does not allow capturing temporal variations explicitly, we introduce an accessibility

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constraint capturing seasonal and inter-annual variations of river discharge. We use the coefficient of variation (CV) of monthly discharge over a reference period of 30 years (here: 1980–2010) assuming a functional relationship that leads to a decrease in accessibility with increasing long-term temporal variability of discharge (see Equation 8).

$$a_c = 2^{\frac{\sigma_c}{\mu_c}} \tag{8}$$

a_c is the share of discharge in cell c that can be accessed, σ is the standard deviation of long-term monthly discharge in cell c and μ_c is the mean discharge of cell c over the same long-term period. The CV is the ratio of the two $\left(\frac{\sigma_c}{\mu_c}\right)$. For more details on the accessibility constraint see Supporting Information S1.

For new irrigation locations, determined in the Surplus Water Allocation Algorithm, we reduce water available for irrigation by $1 - a_c$. For current human abstractions (accounted for in the Actual Human Water Use Accounting, see Section 2.2), it is assumed that efforts of making hardly-accessible water accessible (e.g., by building dams and reservoirs) are already in place, such that all locally available discharge can be used.

2.4. Potentially Irrigated Areas

Based on the allocated and reserved discharge per cell, crop water requirements of the grid cell specific crop mix, as well as the (potentially) available cropland area per cell, we calculate how much area could potentially be irrigated per cell (PIA in Figure 1). In terms of available cropland area, we differentiate current cropland and potential cropland. On land that is currently cropped, we determine the crop mix based on the share of the crop categories grown in 2010 according to our disaggregation using country-level FAOSTAT harvested areas and the spatial distribution of LUH2 crop types (see Section 2.2 and Supporting Information S1). On potential cropland where no such information is available, we assume a crop mix of rapeseed, maize, and pulses, a mix of C3, C4, and N-fixing crops. The current cropland extent is based on LUH2 (see Section 2.2 and Supporting Information S1). We refer to "potential cropland" as the area that is suitable for irrigated crop production according to Zabel et al. (2014)'s global agricultural suitability data set that determines suitability for agriculture based on local topography, soil and climatic conditions. Land classified as marginal (suitability index 0–33) even under irrigated conditions, is excluded from the analysis.

2.5. Scenario Description

In this study, we analyze PIWW, PIWC, and PIA for a set of scenarios presented in the scenario matrix (Figure 3), which is organized along two dimensions: area available for irrigation as well as water and land (protection) constraints. In terms of the area available for irrigation, we differentiate currently irrigated area (IRR-), available current (rainfed and irrigated) cropland areas (CUR-) and areas that are suitable for agricultural production (POT-). In terms of water and land constraints, we differentiate five scenarios (NOLIM, UNSUS, WATSUS, LANDSUS, SUS).

In the water protection scenario (WATSUS), a quantitative restriction of water withdrawals ensures that minimum flows are maintained to preserve a "fair" aquatic and riverine ecosystem status that relies on low- and high-flow requirements (Smakhtin et al., 2004). Protection of EFR in our study assumes that the required minimum flow can be released from reservoirs under water management (Richter & Thomas, 2007; Yin et al., 2011). In the land-related protection scenario (LANDSUS), we assume that no irrigation can take place in priority areas for conservation to safeguard freshwater ecosystems. Priority areas for conservation in this study are based on the Half Earth protection map, which follows a strict conservation objective to protect at least 50% of the land surface in each eco-region, in order to reduce human pressure at half of the Earth's land surface (Immovilli & Kok, 2020; Kok et al., 2020; Kopnina, 2016; Wilson, 2017). The LANDSUS scenario therefore delineates a conservative bound for the sustainable expansion of irrigated cropland into natural land. The Half-Earth area map is provided by Kok et al. (2020). For a detailed description of the data, see Supporting Information S1. As compared to WATSUS, which focuses on water quantity, LANDSUS emphasizes the conservation of (intact) ecosystems by preventing irrigation area expansion and water abstractions in areas of ecological importance. The SUS scenario combines the land and WATSUS, such that both environmental flows are preserved and irrigation is limited to areas that do not fall into these special ecological zones. In the UNSUS scenario, neither land nor water resources

Sustainability & Water Constraint \ Available area for irrigation	Irrigation only allowed on currently irrigated areas	Irrigation allowed on all of current cropland	Irrigation allowed on all suitable land for agricultural production
No water limitation	IRR-NOLIM	CUR-NOLIM	POT-NOLIM
Constrained by local water availability	IRR-UNSUS	CUR-UNSUS	POT-UNSUS
Constrained by local water availability & respecting environmental flow requirements	IRR-WATSUS	CUR-WATSUS	POT-WATSUS
Constrained by local water availability & excluding protected land from irrigation expansion	IRR-LANDSUS	CUR-LANDSUS	POT-LANDSUS
Constrained by local water availability & respecting environmental flow requirements & excluding protected areas from irrigation expansion	IRR-SUS	CUR-SUS	POT-SUS

Figure 3. Scenario overview.

are protected, but irrigation is constrained by local water availability. The NOLIM scenario provides a hypothetical maximum area that would be available for irrigation without considering local water constraints or protection scenarios.

All scenarios are calculated for different yield gain thresholds and for one scenario where the reservation of current agricultural water uses is activated as well as one where it is deactivated such that irrigation potentials are purely determined by the economic cell ranking. The reservation of current agricultural water uses is relevant because currently irrigated areas already have irrigation infrastructure (such as reservoirs and canals) in place that divert natural river flows (Biemans et al., 2011; Veldkamp et al., 2018; Wada et al., 2013) and therefore affect water availability and irrigation potentials for other grid cells. It is helpful for analyses where current irrigation patterns should be maintained, for example, for the initialization period of global LSMs to meet observed irrigated areas in the initialization year. In this study, they are calculated to show the potential expansion of currently irrigated areas on current cropland and on potential cropland beyond already irrigated areas (see Figure 5). All other results in this study, focusing on an efficient allocation (economic irrigation potentials; PIA curves), are provided without this constraint.

3. Results

3.1. Current Irrigation and Irrigation Potentials on Currently Irrigated Areas

We estimate that a consumptive water volume of 939 km^3 yr^{-1} is required to irrigate the given cropmix on all global currently irrigated areas (265 Mha) (see also full summary table in Supporting Information S2). The share of current irrigation water demand under full irrigation requirements that can be fulfilled by locally available renewable water resources captured in our data set is depicted in Figure 4. Areas where not all current irrigation can be fulfilled by the local water resources of this study include mainly the Nile river basin in Egypt, North-West India and Pakistan, North-East China and parts of Central Asia and the Western USA.

Under consideration of an optimal distribution of irrigated areas according to a water productivity ranking, PIA on currently irrigated areas (see IRR-scenarios in Figure 6) would amount to 174 Mha (IRR-UNSUS). If areas of ecological importance were excluded from irrigation, PIA would reduce to 172 Mha (IRR-LANDSUS). Protecting EFR would reduce PIA on currently irrigated areas to 163 Mha (IRR-WATSUS). Under both water and land protection (IRR-SUS), PIA on currently irrigated areas is 162 Mha.

3.2. Technical Irrigation Potentials on Current and Potential Cropland

Figure 5b shows the technical PIA on current cropland, that is, the results of our hydro-economic data processing routine at a yield gain threshold of 0 USD ha^{-1}. In terms of PIA on current cropland, 998 Mha could be irrigated given local water resources (CUR-UNSUS). If irrigation could only expand into cropland outside of

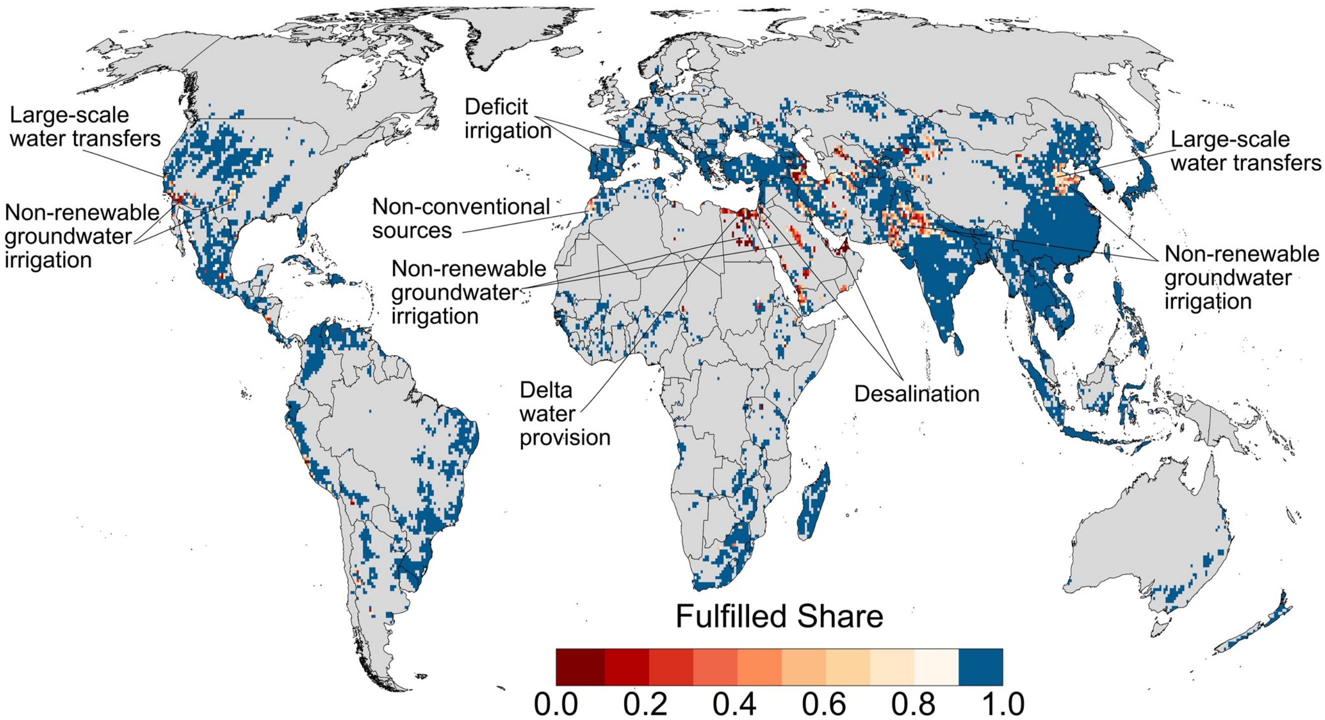

Figure 4. Share of current irrigation water demand under full irrigation requirements (IRR-NOLIM) that can be fulfilled by locally available renewable water resources captured in our data set (IRR-UNSUS) in 2010. Gray areas are currently not irrigated. Cells with very small cropland areas (cropland area share below 1%) are excluded from the visualization. Annotations are potential explanations for unfulfilled current irrigation water.

areas of ecological importance and EFR were maintained (CUR-SUS), 913 Mha could be irrigated (see panel 1b in Figure 6). This area corresponds to about 60% of current cropland (1,531 Mha, CUR-NOLIM) and 648 Mha more than currently irrigated areas (265 Mha, IRR-NOLIM). We find a technical irrigation expansion potential in Europe, Sub-Saharan Africa, Central India, Southern Brazil, and the Western USA (difference between areas in Figures 5a and 5b).

Under cropland expansion into non-protected areas that are suitable for cropland activities under irrigation (a total area of 6,752 Mha), 45% (3,009 Mha, POT-UNSUS) could be irrigated given local water availability. Around 32% (2,144 Mha) could be irrigated within water and land boundaries (POT-SUS). The spatial patterns of unconstrained PIA on all of potential cropland considering today's actually irrigated areas (POT-UNSUS) is depicted in Figure 5c. It shows that there are substantial additional technical irrigation potentials when expanding cropland in South America, Sub-Saharan Africa and South-East Asia.

The respective PIWC on current cropland area considering all technically available local discharge allocated to its most productive use (technical irrigation potential, see panel 2b in Figure 6) amounts to 2,164 $km^3\ yr^{-1}$ (CUR-UNSUS); 1,949 $km^3\ yr^{-1}$ of which could be consumed while maintaining EFR and without irrigation in areas of ecological importance (CUR-SUS). On potential cropland, that is, land that is suitable for agricultural production, 5,289 $km^3\ yr^{-1}$ could be consumed when unregulated, that is, without land and water protection (POT-UNSUS). If EFR were respected, PIWC would be reduced to 4,879 $km^3\ yr^{-1}$ (POT-WATSUS). If ecologically important zones were protected from irrigation, 4,218 $km^3\ yr^{-1}$ would be available for consumptive agricultural water use without explicitly accounting for EFR (POT-LANDSUS). If both land and water protection criteria were respected, 3,888 $km^3\ yr^{-1}$ could be consumed (POT-SUS).

3.3. Economic Irrigation Potentials

Not all technical potential with positive yield gains would be irrigated in reality due to costs for irrigation. Irrigation would only take place where the aggregate yield gain through irrigation exceeds the additional production cost that arise due to irrigation. Figure 6 shows the comparison of the technical potential (for a low threshold of

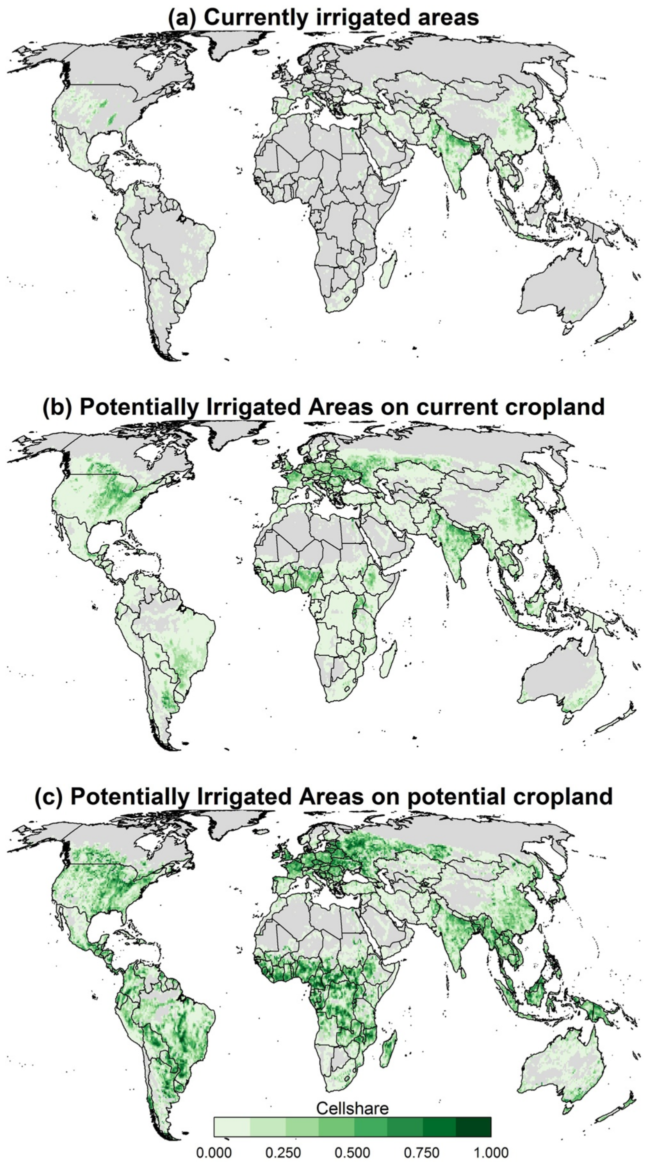

Figure 5. Potentially irrigated areas (PIAs) (as share of grid cell area) for different scenarios (in 2010): (a) Currently irrigated areas (IRR-NOLIM); (b) PIA on current cropland considering already irrigated areas (CUR-UNSUS); (c) PIA on potential cropland considering already irrigated areas (POT-UNSUS). Current agricultural water uses are reserved for this graph to visualize additional potentials beyond currently observed irrigation. Cells with very small potential cropland area (potential cropland area share below 1% of cell area) are excluded from the visualization (gray areas).

0 USD ha^{-1}) and economic irrigation potentials (for a medium threshold of 300 USD ha^{-1} and a high threshold of 600 USD ha^{-1}). While technically, 913 Mha of current cropland could be irrigated sustainably, only 356 Mha achieve a yield gain of at least 300 USD ha^{-1} and only 159 Mha fall into the high yield gain range (above 600 USD ha^{-1}) (CUR-SUS, see Figure 6 panel 1b). On potential cropland excluding areas of ecological importance, the total biophysical PIA allocated to areas above a minimum yield gain threshold of 0 USD ha^{-1} (technical potential) would be 2,144 Mha (POT-SUS in Figure 6 panel 1c). Assuming that irrigation would only be viable economically at a minimum yield gain of at least 300 or 600 USD ha^{-1}, the global PIA would be reduced drastically to 698 or 330 Mha respectively (POT-SUS in Figure 6 1c).

Globally, the simulated yield gain through irrigation differs depending on the location (see also Figure S1b in Supporting Information S1). In areas that are already currently under irrigation, the average yield gain is 1,054 USD ha^{-1}. On currently rainfed cropland, the average yield gain is 500 USD ha^{-1}; and on all potential land suitable for agricultural production, it is 840 USD ha^{-1}. On currently irrigated areas (IRR), the share of PIA and PIWC that falls into high threshold classes (violet and orange bars in Figure 6) is higher than on all (rainfed and irrigated) cropland (CUR) and potentially suitable agricultural areas (POT).

To visualize which areas would be irrigated given different irrigation yield gain thresholds, Figures 7a and 7b show the spatial distribution of PIAs under yield gains greater than 600 USD ha^{-1} (orange areas), smaller or equal 600 USD ha^{-1} and greater than 300 USD ha^{-1} (violet areas) and greater than 0 USD ha^{-1}, but smaller or equal 300 USD ha^{-1} (green areas). In the POT-SUS scenario, a total of 329 Mha fall into the high yield gain range, 372 Mha into the medium yield gain range and 1,475 Mha have a yield value gain below 300 USD ha^{-1}. The global irrigated area for different irrigation yield gains is summarized in the PIA curves shown in Figure 7c. Many of the areas that show high technical irrigation potentials (see Figure 5c) fall into the low yield gain range of 0–300 USD ha^{-1} (green areas in Figure 7) (e.g., Sub-Saharan Africa; South-East Asia; West and Central Latin America). PIA in the high yield gain range (>600 USD ha^{-1}) (orange areas in Figure 7a) are found in the Western USA, Southern Africa, South-East Brazil, Southern Europe and the Middle East and are partly already irrigated today (see Figures 4 and 5a).

The supplementary material to this study includes the full global summary table of irrigation potentials in terms of PIA, PIWC, and PIWW for all scenarios (NOLIM, UNSUS, WATSUS, LANDSUS, SUS) for the area extent of currently irrigated areas (IRR), current cropland area (CUR) and potential cropland area (POT) for the thresholds of 0, 300 and 600 USD ha^{-1}.

3.4. Aggregated Irrigation Potentials

Figure 8 shows PIA curves depicting the marginal return to irrigated area for two levels of aggregation (river basins and countries). Figure 8a shows PIA curves for selected river basins. There are river basins with highly inelastic irrigation area demand (steep PIA curves, e.g., Huang He and Colorado). Other basins are more heterogeneous (e.g., Parana, Ganges and Mississippi); that is, there are both areas with high yield gains and low yield gains in the same basin. Some basins (e.g., Ganges, Indus and Huang He) already today exceed the sustainable irrigation potential on current cropland based on our hydro-economic data processing routine. Furthermore, different bottlenecks can be identified for different basins. The Huang He, Indus and Ganges river basins are water-limited. There is an economic incentive

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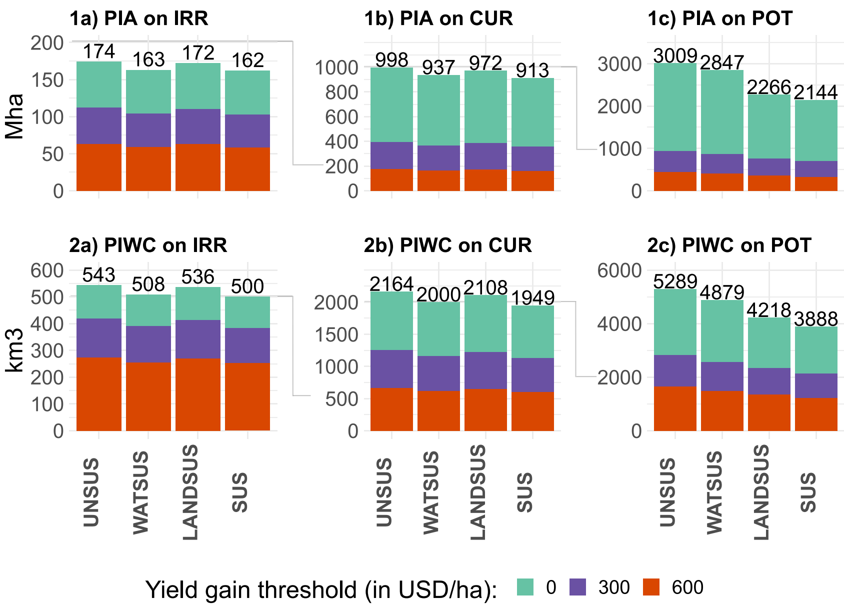

Figure 6. Potentially Irrigated Areas, PIA (1) and Potential Irrigation Water Consumption, PIWC (2) for different land scenarios: (a) Currently irrigated areas (IRR); (b) Total current cropland (CUR); (c) Potential cropland (POT) for different yield gain thresholds.

for irrigation expansion on current cropland (CUR-NOLIM), but local water resources are limited and prevent further irrigation with local renewable water resources (CUR-SUS, CUR-UNSUS), even under cropland expansion (POT-SUS). The currently irrigated areas in these basins already exceed the potential given local renewable water resources, indicating that other forms of water provision (long-distance transports or non-renewable water supplies) are practiced. Other basins (e.g., Parana, Mekong and Chang Jiang) are rather limited in available land. Further sustainable irrigation would be possible if cropland area was expanded.

Figure 8b depicts PIA curves at country-level aggregation. We observe that while Brazil could expand irrigation on current cropland without transgressing the land and water boundaries, India has little to no potential to further increase irrigated areas, even under cropland expansion. It is important to note that aggregated numbers of areas currently irrigated (black triangular in Figure 8) and the PIA shown in the curves can be spatially allocated differently (see Figures 5 and 7).

The supplementary material to this study includes detailed country results for 235 countries and 14 irrigation yield gain thresholds for the full range of scenarios (NOLIM, UNSUS, WATSUS, LANDSUS, SUS and IRR, CUR, POT) both in terms of PIA (in Mha) as well as PIWC and PIWW (in $km^3\ yr^{-1}$). Both irrigation potentials with reserved currently irrigated areas as well as purely yield-gain-determined irrigation potentials are provided.

4. Discussion

4.1. Current Irrigation

In our study, the currently irrigated areas (265 Mha) correspond to PIWC of 939 $km^3\ yr^{-1}$. This value falls into the range of previous ensemble studies by Hoff et al. (2010) and Haddeland et al. (2014) that find current global irrigation water consumption in a range between 927–1,530 and 940–1,284 $km^3\ yr^{-1}$, respectively. The spatial distribution of areas where current irrigation water cannot be served by local renewable water resources (red areas in Figure 4) is similar to the areas that suffer under extreme blue water over-use (see Figure 3e in Rost et al. (2008)), groundwater depletion (see Figure 1c in Wada et al. (2010)) and to the areas that face water scarcity and unsustainable water use in parts of the growing period found in Rosa, Chiarelli, Rulli, et al. (2020).

Some of the areas that are currently under irrigation rely on non-renewable groundwater irrigation (e.g., India and Pakistan, Siebert et al., 2010; Wada et al., 2012), non-conventional sources (e.g., Morocco and Arab Peninsula, Hssaisoune et al., 2020; Lattemann et al., 2010), or large-scale water transfers (e.g., China and USA, Grigg, 2021;

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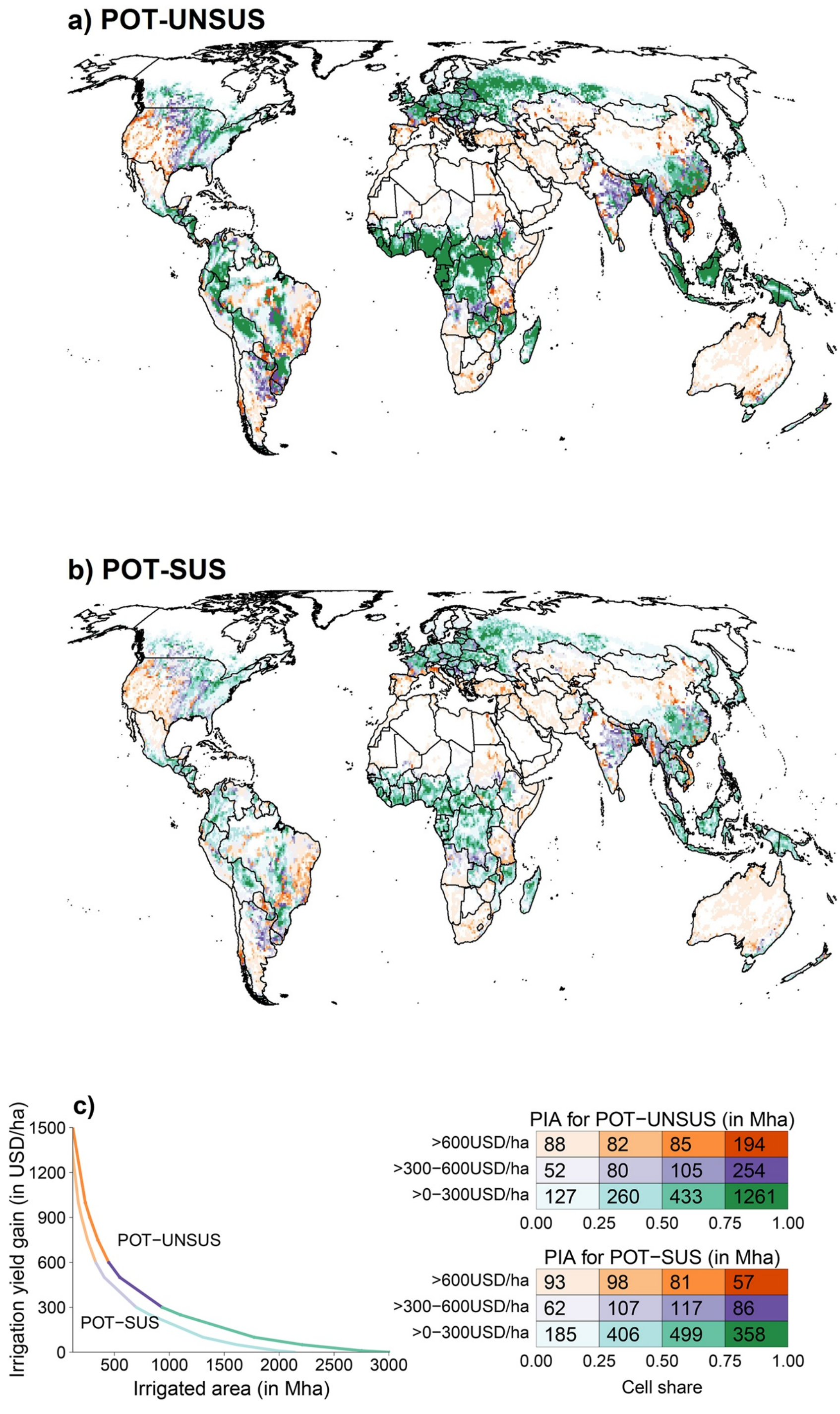

Figure 7. Potentially irrigated areas (PIA) in 2010 (displayed as share of the grid cell area) for three different yield gain thresholds (0, 300, 600 USD ha−1) on potential cropland for two scenarios (POT-UNSUS; POT-SUS). Cells with very small potential cropland area (potential cropland area share below 1% of cell area) are excluded from the map visualization. Orange areas: PIA with yield gains >600 USD ha^{-1}. Violet areas: PIA with yield gains between >300 and 600 USD ha^{-1}. Green areas: PIA with yield gains between >0 and 300 USD ha^{-1}. Legends show the global sum of potential cropland (in Mha) that falls into each category.

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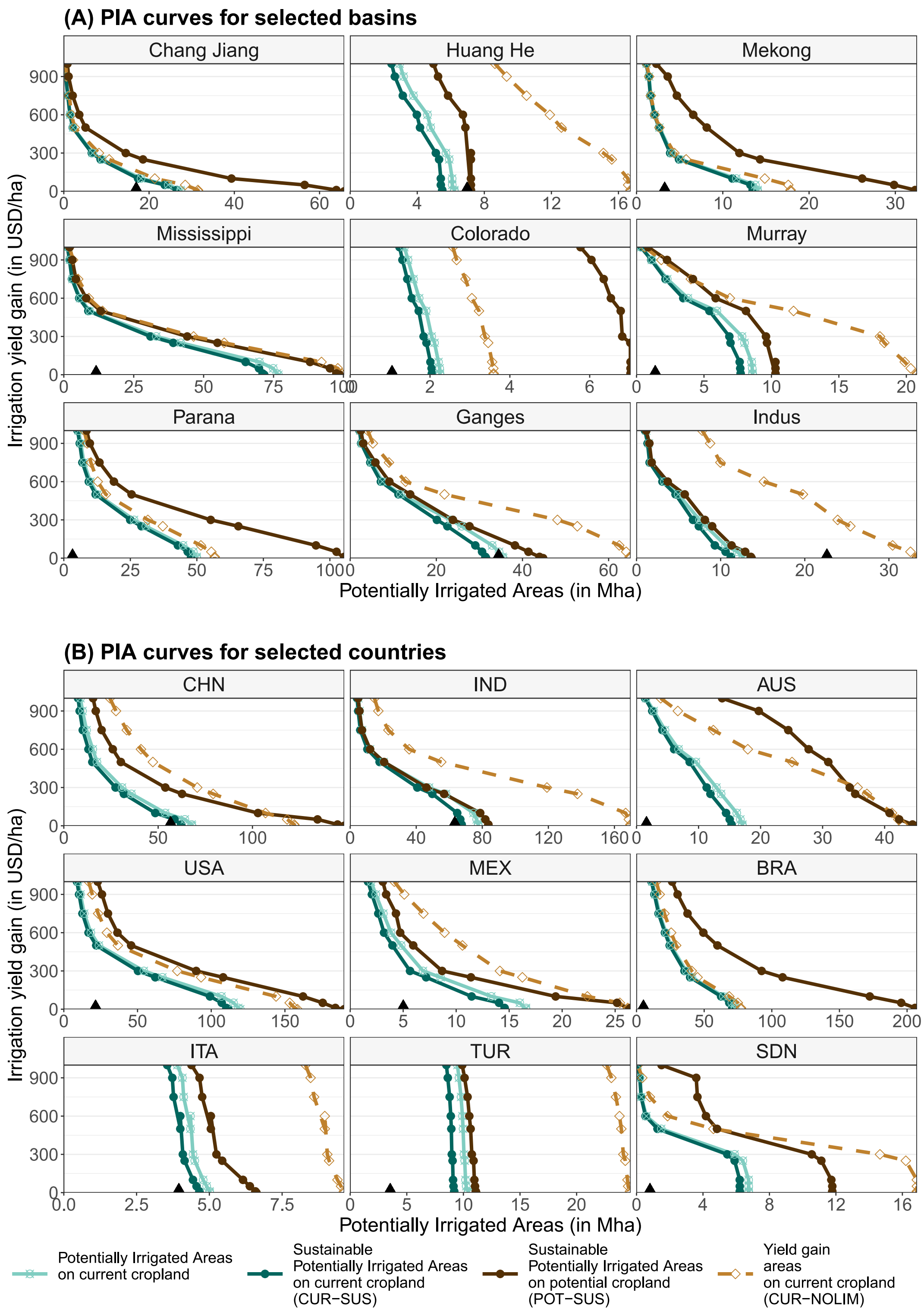

Figure 8. Marginal yield gain for potentially irrigated areas (in 2010) of (a) selected river basins and (b) selected countries (abbreviated in titles by iso3 country codes) for the non-water limited scenario (NOLIM), the protection scenario (SUS) and the scenario without land and water conservation (UNSUS) on current cropland (CUR) and the protection scenario (SUS) on potential cropland (POT). The black triangular symbol indicates area that is currently reported to be irrigated.

Rogers et al., 2020). Their water requirements could not be fulfilled by local renewable water available according to our estimate (see Figure 4). This is also visible in Figure 8 depicting PIA curves for selected basins and countries. In some basins (e.g., Ganges, Indus and Huang He), the currently irrigated area exceeds the PIA in water-limited scenarios on current cropland (CUR-UNSUS as well as CUR-SUS). There are, however, yield gains through irrigation, as indicated by the CUR-NOLIM scenario. Such areas are at risk to over-exploit their water resources when following profit maximization criteria without implementing protection policies and partly already today rely on non-renewable or non-conventional water withdrawals or large-scale transfers (Rogers et al., 2020; Siebert et al., 2010).

4.2. Potentially Irrigated Areas and Expansion Potential

Globally, we find technical sustainable irrigation potentials on current cropland of 913 Mha (CUR-SUS) and 2,144 Mha on potential cropland (POT-SUS). Our results show large technical irrigation expansion potential on current cropland (see Figures 5a and 5b), for example, in several countries of Sub-Saharan Africa and Northern Europe, South-East Brazil and Central India. However, in many of these areas the yield gain through irrigation falls into the lower range (<300 USD ha^{-1}) (e.g., Sub-Sahran Africa and Northern Europe; see Figure 7). These areas would only be irrigated if cost for irrigation were low or irrigation would be subsidized. Especially in Sub-Saharan Africa irrigation costs are reported to be very high (Inocencio et al., 2007; Jones, 1995) (see also Table S1 in Supporting Information S1). This explains the discrepancy between observed irrigation and the technical irrigation potential on current cropland in this region and is in line with previous findings in the literature (You et al., 2011). Our spatially explicit and country- as well as basin-level analysis reveals that there are high yield gains from irrigation in Eastern Brazil, Western and Central USA and Northern India. However, many of these areas would face a reduction of PIA when land and water conservation goals are respected (see Figures 7a and 7b). These high opportunity costs may make land and water protection particularly challenging.

4.3. Planetary Water Opportunities in Terms of Potential Irrigation Water Consumption

Our global PIWC serves as an estimate of a global "planetary water opportunities" boundary (Gerten et al., 2011). As opposed to previous top-down estimates of the planetary boundary (PB) for water (Rockström et al., 2009), our PIWC estimate is grounded in spatially explicit data and takes societal water needs into account via the water productivity ranking algorithm and spatially explicit accounting of human water demands. With 4,079 km^3 yr^{-1} (3,888 km^3 yr^{-1} (PIWC in POT-SUS) + 191 km^3 yr^{-1} (exogenous non-agricultural water consumption)), it falls into the uncertainty range of the PB for water (1,100–4,500 km^3 yr^{-1}) suggested by Gerten et al. (2013). Furthermore, it accounts for land conservation besides the consideration of spatially explicit EFR. The isolated estimates of PIWC when only environmental flows are protected of 4,879 km^3 yr^{-1} (POT-WATSUS) and 4,218 km^3 yr^{-1} under protection of areas of ecological importance only (POT-LANDSUS), and their combined effect resulting into 3,888 km^3 yr^{-1} (POT-SUS) shows that there are likely synergies between the land, water and biodiversity PBs (Rockström et al., 2009).

With the consideration of a range of economic thresholds, our assessment goes beyond the assessment of technical potentials and accounts for societal water demands. The levels calculated in our IRR-WATSUS and CUR-WATSUS as well as CUR-UNSUS scenarios are comparable to water consumption limits found in Jenkins et al. (2021), who account for different "values of water" beyond biophysical aspects on current cropland. Our study goes beyond this estimation by providing planetary water opportunity boundaries for all of potential cropland. While a total volume of 5,289 km^3 yr^{-1} (POT-UNSUS) could technically be consumed in irrigated agriculture, not all of this would actually be consumed when considering economic yield gain thresholds. With a minimum yield gain of 300 (600) USD ha^{-1}, PIWC would only be 2,826 (1,644) km^3 yr^{-1} (POT-UNSUS) according to our estimate. Under these thresholds, the "sustainable" PIWC would drop from 3,888 km^3 yr^{-1} (technical potential) to 2,121 (1,219) km^3 yr^{-1} (economic potential).

4.4. Environmental Constraints

Our land and water limits are quantitative resource use constraints. While our strict land conservation approach—protecting 50% of the land surface—captures one important dimension of biodiversity protection (prevention of intensification by irrigation in conservation priority areas), other land conservation dimensions (e.g., land

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connectivity (Ward et al., 2020)) are not accounted for. Similarly, the restriction of long-term total water volumes as minimum flow requirements falls short of accounting for important aspects to keep riverine ecosystems intact (e.g., the timing of extreme low and high flows that fulfill important functions for habitat formation or riparian vegetation through sediment or organic material flushing (Yin et al., 2011)). Existing globally applicable approaches do not account for such detail and only provide estimates of long-term average flow requirements (Pastor et al., 2014). Furthermore, the impact of river fragmentation through dams and reservoirs on aquatic biodiversity is ignored (Lehner et al., 2011; Nilsson et al., 2005), and the impact of irrigation on water quality (van Vliet et al., 2017, 2021) as well as soil quality (Khan et al., 2006) is not considered. This implies that we tend to over-estimate water availability within environmental limits because the estimated EFR budgets have to be actively managed to fulfill such riparian ecosystem health functions. This requires to set aside reservoir storage for EFR management (Richter & Thomas, 2007; Yin et al., 2011) or, if optimal management cannot be achieved, higher effective EFR budgets. Accordingly, water availability for human uses is affected.

4.5. Temporal Scale

With our approach, it is not possible to explicitly account for temporal flow variations. However, to capture the effect of temporal flow variability on water availability in a simplified manner, we constrain water accessibility in relation to the CV of monthly discharge. This accounts for the combined effect of both intra-annual and inter-annual flow variations. We implicitly assume that dams and reservoirs are used to balance water provision throughout the year such that (a) it is available at the time of the year when it is needed (cf. Jenkins et al. (2021)), and (b) environmental needs are provided as part of the water management plan (cf. Richter and Thomas, 2007; Yin et al., 2011).

Renewable groundwater is included in the cell water balance (Rost et al., 2008). However, due to the omission of temporal flow variations, the role of groundwater as a natural reservoir that buffers flow variability is not accounted for. This tends to lead to an under-estimation of water accessibility and irrigation potentials in locations where renewable groundwater provides a stable source of renewable water (cf. de Graaf and Stahl, 2022).

4.6. Economic Aspects

Because the objective of this study is to provide a benchmark estimate that uses inter-comparable criteria between administrative boundaries, we do not account for institutional and political barriers that impede irrigation (Boelens et al., 2016; Rosa, Chiarelli, Rulli, et al., 2020). Our analysis does not cover market distortions, like subsidies, that in reality facilitate irrigation in areas where it would hardly be profitable (Dinar et al., 1997). This may also partly explain the difference between the technical potential on actually irrigated areas of 174 Mha (IRR-UNSUS) and the corresponding economic potentials of 112 Mha at a yield gain threshold of 300 USD ha^{-1}, and 63 Mha at a yield gain threshold of 600 USD ha^{-1}. We find that, on average, the yield gain in irrigated areas is higher than in areas that are not yet under irrigation. Nevertheless, some areas are irrigated even though they fall below the yield gain thresholds chosen in this study.

The economic irrigation potential is based on simplified economic thresholds highlighting where irrigation is beneficial when considering the current crop composition and respecting local water constraints. In order to correct for value differences of different crops and to make different grid cells with different crop compositions internationally comparable, we use global average commodity prices for major crops. While using national prices may better reflect the current economic allocation, for our potentials study it is more appropriate to compare different irrigation locations on equal terms. If our data set is applied for future scenarios with expansion of crop production and irrigation or a shift in crop composition or irrigation efficiency, prices could change and therefore, in turn, affect future yield gains (Calzadilla et al., 2011). To account for price feedbacks, our new method can be coupled and iterated with an economic land-system model that covers agricultural irrigation and future land-use change. Furthermore, our open-source model is flexible to alternative settings (e.g., with respect to commodity prices) if the modeling context or research question demands so. Our sensitivity analysis (see Supporting Information S1) has shown that the observed patterns are relatively robust against price changes.

4.7. A Novel Water Input Aggregation Method for Land-System Models

The objective of the estimation of the hypothetical irrigation potential on all potential cropland is to provide an option space in terms of PIA to global Land-System Models (LSMs) that optimize land-use patterns given future food demand considering the trade-off between intensification and cropland expansion (e.g., MAgPIE (Biewald et al., 2014), GLOBIOM (Pastor et al., 2019), GTAP-W, SIMPLE-G (Calzadilla et al., 2010; Liu et al., 2017)). Our estimated potentials should not be interpreted as a normative proposal to expand irrigated areas. Besides irrigation water availability as well as water and land constraints, many other criteria such as food requirements, greenhouse gas policies and other sustainability goals need to be considered. These aspects are considered in integrated LSMs. Such models can be used to assess if and where irrigated crop production may take place under different scenarios. However, the consideration of upstream-downstream relations of water resources is challenging for global LSMs because of their level of aggregation. For data availability and computational reasons, global-scale economic models assessing optimal land-use patterns under environmental constraints run at an aggregated scale of spatial clusters, nations or world regions (e.g., Dietrich et al., 2019; Pastor et al., 2019; Woltjer and Kuiper, 2014). They usually lack a hydrologically-founded spatial representation of the interaction of water availability, potential cropland area, water abstractions, and the accompanying upstream-downstream effects. When different data sets (such as water availability, land suitability, information on protected areas, and non-agricultural water demands) are aggregated independently, their interaction is lost. For example, despite sufficient water and cropland availability in the aggregated cluster, the suitable land might not be close enough to the water source for irrigation. In this context, our global hydro-economic data processing routine provides a valuable hydrological input aggregation and output disaggregation tool to global LSMs.

4.8. Limitations

Mismatches of current observed irrigation and the estimated irrigation patterns using local renewable water availability can be explained by our modeling assumptions with regards to water transport, deficit irrigation, and the focus on natural renewable water sources for irrigation.

The objective of this study is to represent long-term irrigation potentials from renewable water resources. Therefore, we neither include groundwater depletion (groundwater over-exploitation and fossil groundwater resources) nor non-conventional sources (wastewater reuse and desalination) in the water availability assessment. This can explain mismatches of current water supply and demand (see Figures 4 and 8) in Morocco (Hssaisoune et al., 2020), California (USA), Saudi Arabia (Chandrasekharam, 2018; Scanlon et al., 2012), Kuwait, Qatar, United Arab Emirates, Israel (Lattemann et al., 2010; Siebert et al., 2010) as well as regions that rely heavily on non-renewable groundwater irrigation (e.g., northern India, Pakistan, North-East China, western USA (Rodell et al., 2018; Rogers et al., 2020; Siebert et al., 2010; Wada et al., 2012)).

In our model, water transfers can only take place within the respective 0.5°grid cell. This implies a maximum water transport distance of around 78 km at the equator and decreasing transport distance towards the poles. Therefore, no large-scale water transport is allowed. In reality, however, long-distance water pipelines or canals exist; for example, the South-North Water Transfer Project that supplies drinking and sanitary water to cities in North-East China (Rogers et al., 2020) or California's State Water Project that serves farmers and households in the dry regions of California (Grigg, 2021). Similarly, regions where river deltas provide water for irrigation are misrepresented because the global river drainage network data set (STN-30p) does not consider deltas (i.e., one grid cell cannot discharge into several downstream grid cells) (Lehner et al., 2011; Vörösmarty et al., 2000, 2011). This explains the water deficits as observed in the Nile delta (Figure 4).

An additional complexity that we do not consider is deficit irrigation, an irrigation practice that is observed in reality in areas where water supply is limited and the marginal costs for water would be high (Geerts & Raes, 2009). Whether and to which degree deficit irrigation would be applied depends on the ratio between variable costs (water and pumping costs) and fixed costs (dams, reservoirs, channels, equipment), with high variable costs being an incentive for deficit irrigation, while high fixed costs are an incentive for full irrigation (English, 1990). A comprehensive assessment of deficit irrigation would therefore require spatially explicit information on the relative difference between variable water costs and fixed investment costs, as well as yield-water response curves that are crop- and location-specific. By omitting deficit irrigation, our algorithm over-estimates the water requirements and therefore under-estimates the respective PIA in water-limited locations. The Supporting Information S1 provides an extended discussion of this aspect.

Lastly, the potential of irrigation to enable additional cropping seasons (multiple cropping) in subtropical and tropical regions (Waha et al., 2020) is not captured in our model. LPJmL provides irrigation water requirements and yields for a single cropping season under irrigated and rainfed conditions respectively. It accounts for potential shifts in the growing period due to irrigation, but does not include the potential of an additional growing cycle within the same year (e.g., by irrigation during the dry season). This implies that we underestimate the irrigation potential in regions where multiple cropping is prevalent (e.g., in East and South Asia (Waha et al., 2020)). It is an aspect that is ignored in most global irrigation assessments and LSMs and should be addressed in future research.

5. Conclusion

Our spatially-explicit irrigation water processing routine captures local hydrological information and water abstractions for human uses along rivers to derive potentially irrigted areas and potential irrigation water withdrawals and consumption taking upstream-downstream effects explicitly into account. We find large untapped irrigation potentials within local land and water boundaries both on current cropland (913 Mha; CUR-SUS scenario) and on potential cropland (2,144 Mha; POT-SUS) (e.g., large parts of the African continent, South-East Brazil and Southern China). Not all of these technical irrigation potentials are viable due to irrigation costs (e.g., Sub-Saharan Africa). Globally, the irrigation potential of 913 Mha on current cropland (CUR-SUS) would reduce to 356 Mha if only areas with yield gains of at least 300 USD ha^{-1} would be irrigated and only 172 Mha have yield gains of at least 600 USD ha^{-1}.

There is a financial incentive to irrigate areas that should be protected from irrigation due to their importance for conservation efforts and where minimum environmental flows should be maintained. Because of the ecological consequences of cropland expansion and intensification, land- and water-conservation policies are important to prevent water overuse; especially in highly productive areas. Examples of areas where protection policies are important to prevent unsustainable irrigation expansion (beyond land and water boundaries) are Eastern Brazil, Western and Central USA and Northern India. We also find that some countries or river basins have an incentive to apply unconventional irrigation practices, given the amount of areas that show high yield gains, but are water- and land-limited (e.g., the Huang He, Ganges or Indus river basins). In parts, these areas already rely on non-renewable groundwater for irrigation (e.g., India) or installed large-scale water transfer infrastructure (e.g., Huang He river basin in China) in order to close the gap.

Together with future climatic and socio-economic scenarios and simulated data on required inputs such as non-agricultural water uses, the irrigation potentials calculated by our new processing routine can be used to inform global land-system models on local water availability in the present and the future. Further, they can provide spatially explicit information on potential irrigation patterns and irrigation area expansion. The method can be used as a tool to aggregate hydrological input data to the required simulation unit and to disaggregate land-system model outputs (such as irrigation withdrawals) to a high spatial resolution. This can help to address water- and irrigation-specific research questions across different scales in a global context.

Acknowledgments
FDB was funded by the German Federal Environmental Foundation (Deutsche Bundesstiftung Umwelt, DBU) under the Grant AZ20018/557 and the Food, Agriculture, Biodiversity, Land-Use, and Energy (FABLE) Consortium (FABLE 2.0, Grant 94120). BLB has received funding from the European Union's Horizon 2020 research and innovation program under Grants 776479 (COACCH) and 821010 (CASCADES) and from the German Ministry for Education and Research (BMBF) Grant 01LS2105A (ABCDR). JH acknowledges funding from the German Ministry for Education and Research (BMBF) through the EXIMO project (Grant 01LP1903D). KK was funded through the BMBF under the Grant 01LS2101G (CDRSynTra) and Deutsche Forschungs gemeinschaft (DFG) under the Grant ED78/3-2 (CEMICS2). Funding from the German Federal Ministry of Education and Research (BMBF) in the context of the project "FOCUS—Food security and sustained coastal livelihoods through linking land and ocean" (031B0787B) is gratefully acknowledged. We would like to thank Dirk Biermann for consultations to the figure design of this article. Open Access funding enabled and organized by Projekt DEAL.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The open-source code (Beier et al., 2021) is developed on github (https://github.com/pik-piam/mrwater/) and available at https://doi.org/10.5281/zenodo.7572684. The script used to visualize results for the purpose of this publication is published in the github repository https://github.com/FelicitasBeier/IrrigationPotentials. The respective data used was created with the code published at https://doi.org/10.5281/zenodo.7572684 and is available at https://doi.org/10.5281/zenodo.7572847.

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