



Mapping irrigation potential from groundwater in Africa

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Mapping irrigation potential from renewable groundwater in Africa – a quantitative hydrological approach

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Abstract

Groundwater provides an important buffer to climate variability in Africa. Yet groundwater irrigation contributes only a relatively little share of cultivated land, approximately 1% (about 2 million hectares) as compared to 14% in Asia. While groundwater is over-exploited for irrigation in many parts in Asia, previous assessments indicate an under-utilized potential in parts of Africa. As opposed to previous country-based estimates, this paper derives a continent-wide, distributed (0.5° spatial resolution) map of groundwater irrigation potential, indicated in terms of fractions of cropland potentially irrigable with renewable groundwater. The method builds on an annual groundwater balance approach using 41 years of data, allocating only that fraction of groundwater recharge that is in excess after satisfying other human needs and environmental requirements, while disregarding any socio-economic and physical constraints in access to the resource. Due to high uncertainty of groundwater environmental needs, three scenarios, leaving 30, 50 and 70% of recharge for the environment, were implemented. Current dominating crops and cropping rotations and associated irrigation requirements in a zonal approach were applied in order to convert recharge excess to potential irrigated cropland. Results show an inhomogeneously distributed groundwater irrigation potential across the continent, even within individual countries, reflecting recharge patterns and presence or absence of cultivated cropland. Results further show that average annual groundwater available for irrigation ranges from 692 to 1644 km³ depending on scenario. The total area of cropland irrigable with groundwater ranges from 27.2 to 64.3 million ha, corresponding to 12.5 to 29.6% of the cropland over the continent. The map is a first assessment that needs to be complimented with assessment of other factors, e.g. hydrogeological conditions, groundwater accessibility, soils, and socio-economic factors as well as more local assessments.

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1 Introduction

Irrigation expansion is seen as a significant leverage to food security, livelihoods, rural development, and agricultural and broader economic development in Africa, especially in sub-Saharan Africa (SSA). National and regional (CAADP, 2009; NEPAD, 2003) policies and plans stress irrigation development, and more broadly sustainable land and water management, as a key component to poverty alleviation and gains in food productivity. FAO (2005) assessed the potential for irrigation development¹ in Africa to be 42.5×10^6 ha, corresponding to 20.1 % of the cultivated area or 5.7 % of the cultivable land. While still playing a secondary and minor role in national and regional plans, groundwater is increasingly included as a viable and suitable supplementary or sole resource to develop for irrigation along with traditional surface water resources (MoAC, 2004; MoFA and GIDA², 2011; MoFED, 2010; MoIWD, 2005; MoWEA, 2013). This is explained by evidence that farmers progressively embrace groundwater irrigation (GWI) spontaneously and with own investments where conditions permit (Villholth, 2013) and the notion that the groundwater resources in Africa generally are plentiful as well as underutilized (MacDonald et al., 2012).

Groundwater irrigation presently covers around 2×10^6 ha in Africa, equivalent to 1 % of the cultivated land (Siebert et al., 2010). In Asia, similar figures amount to 38×10^6 ha or 14 % of cultivated land (Siebert et al., 2010). Hence, it is fair to assume that there is appreciable scope for further developing GWI in the continent. Barriers to an expansion of groundwater-based irrigation in Africa, and in particular SSA, include

¹Definition of irrigation potential in FAO (2005): area of land (ha) which is potentially irrigable. Country/regional studies assess this value according to different methods, for example some consider only land resources suitable for irrigation, others consider land resources plus water availability, others include in their assessment economic aspects (such as distance and/or difference in elevation between the suitable land and the available water) or environmental aspects, etc.

²In the Ghana National Irrigation Policy, groundwater irrigation falls under the category “informal irrigation”.

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2 Methodology

Following the approach of Pavelic et al. (2013), the methodology assumes groundwater as the sole source of irrigation water and hence gives an estimate of the area that could potentially be irrigated by groundwater disregarding any existing irrigation, whether from groundwater or surface water. Importantly, the method considers only sustainable GWI from a resource perspective, i.e. the use of only renewable groundwater for human needs (including irrigation) while partially satisfying environmental requirements from this renewable resource. As a consequence, non-renewable (fossil) groundwater is not considered available, preventing long-term aquifer depletion.

The water balance assessment is based on a GIS analysis and mapping with a final resolution of 0.5° assuming each cell (about 50 km x 50 km) to be homogeneous and independent of other cells, i.e. no lateral flows occur between cells. For each cell, the GWIP [L^2] is calculated as the potential cropland area that the available groundwater resource can irrigate:

$$GWIP = \frac{GW \text{ Available}}{\text{Irrig. Water Demand}} \quad (1)$$

where groundwater availability [$L^3 T^{-1}$] is calculated as any excess of groundwater recharge, considering other groundwater demands from humans (domestic uses, live-stock, industry) and the environment:

$$GW \text{ Available} = GW \text{ Recharge} - \text{Human GW Demand} - \text{Environ. GW Req.} \quad (2)$$

The gross irrigation water demand [$L T^{-1}$], which represents the groundwater abstraction needed to satisfy the deficit rainfall and the irrigation losses, is determined by:

$$\text{Irrig. Water Demand} = \frac{\sum_{i=1}^n (\text{Crop Water Demand}_i \times [\% \text{ of Area}]_i) - \text{Green Water}}{\text{Irrig. Efficiency}} \quad (3)$$

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The equation parameters are given as follows:

- Crop Water Demand [$L T^{-1}$] represents the amount of water needed by the crop to grow optimally during the months of its growing period, independently of the water source and considering water as the only limiting factor for optimal growth (FAO, 1986).
- Green Water [$L T^{-1}$] is the water available for the plants naturally and indirectly from the rainfall through soil moisture.
- % of Area [–] is the areal fraction of a specific crop relative to the total cropland.
- n [–] is the number of crops grown within the grid cell.
- Irrig. Efficiency [–] is the irrigation efficiency coefficient. It is used to express the fraction of groundwater abstracted that is not lost along the water transport from the abstraction point to the crop (FAO, 1989). The extracted groundwater quantity does not reach fully the crops because of transport losses or losses in the field. The return flow to groundwater is considered lost for irrigation (i.e. not included in the recharge, see below) to not overestimate the groundwater availability.
- GW Recharge [$L^3 T^{-1}$] is the net groundwater recharge. It corresponds to the total quantity of water from rainfall which reaches the aquifer.
- Human GW Demand [$L^3 T^{-1}$] is the groundwater use for anthropogenic activities, such as domestic and industrial water supply and livestock watering. Domestic and industrial water requirement are assumed to come partly from groundwater while livestock watering is assumed to be fully supplied by groundwater (see also Sect. 3.3).
- Environ. GW Req. [$L^3 T^{-1}$] is the quantity of water coming from groundwater, which is directly linked to the environment for maintaining ecosystems. This includes river baseflow and groundwater influx to wetlands.

The proposed approach, taking annual water balances, yields an estimate of GWIP with respect to historic hydrology when averaging the assessment over a number of years with varying rainfall and recharge over the continent. This is described in more detail in the next section.

3 Data sources and preparation

3.1 Hydrological data

Data on recharge (GW Recharge, Eq. 2) and green water (Green Water, Eq. 3) derive from model outputs from the PCR-GLOBWB global hydrological model (Van Beek et al., 2011). Data for Africa from a global simulation with 0.5° spatial resolution for a recent 41 year period (January 1960 to December 2000) have been used (including Madagascar, but excluding the smaller islands of Comoros, Mauritius, Seychelles, and Cape Verde). The model calculates for daily time steps the water storage in two vertically stacked soil layers and an underlying groundwater layer, as well as the water exchange between the layers and between the top layer and the atmosphere (rainfall, evaporation and snow melt). The model also calculates canopy interception and snow storage. During the simulation period, land cover changes are not taken into consideration. For the green water availability, the sum of the simulated actual transpiration of the two soil layers under non-irrigation conditions was used. This conservative approach, disregarding soil evaporation, allows not overestimating the availability of water for the crops (Van Beek et al., 2011).

3.2 Crop and irrigation data

The necessary crop data to calculate irrigation water demand (Irrig. Water Demand, Eq. 3) relate to the crop distribution across the continent, the crop calendar over the year, encompassing one or a maximum of two crops per year for any area, and the annually accumulated monthly crop water demand for each crop in each cell. For the

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crop distribution, data for the 2000 crop distribution has been used (Monfreda et al., 2008; Ramunkutty et al., 2008). Figure 1 shows the cropland (217×10^6 ha) distribution in Africa. This includes the cultivated (i.e. harvested) cropland and non-cultivated cropland in 2000.

Six major irrigated crop groups, accounting for an average of 84 % of the total harvested cropland in 2000 (165.7×10^6 ha) over the continent, were considered (Table 1). These include: cereals, oils, roots, pulses, vegetables and sugar crops (sugarcane mostly in Africa). The proportion of the land area occupied by the different crop groups is shown in Fig. 2.

In certain areas, the aggregated crop group areas accounted for more than 84 % of the harvested cropland. This is because double cropping occurs. Hence, in order to assure that double cropping does not entail exaggerated cropland areas, the crop group areas were downscaled by cell-by-cell factors, making the aggregated crop group area for those cells equal to 84 % of the harvested cropland.

For the crop calendar, Africa can be divided into 23 irrigation cropping pattern zones, within which crop calendar, irrigation method and cropping intensity can be assumed to be homogeneous within the cropland (FAO, 1997) (Fig. 3). This subdivision is applied in this study.

The crop calendar data have been extracted from the FAO crop calendar³ and other sources (FAO, 1992, 1986) and compiled into a calendar per crop group done for each irrigation cropping pattern zone. The calendar indicates the specific crops present in the group for each irrigation cropping pattern zone (Supplement). Up to two specific crops from the same crop group can be cultivated per year on the same cropland and allows an annual cropping rotation.

The monthly crop water demand for each crop is determined by disaggregating total (for one cropping season) crop water demand for that crop and knowledge of its crop calendar (Supplement). The seasonal crop water demand, growing periods and

³<http://www.fao.org/agriculture/seed/cropcalendar/welcome.do> (last access: 31 March 2014)

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associated single crop coefficients (K_c) for the various crops are extracted from the literature (FAO, 1992, 1986). Since the crop calendar includes entries with more than one specific crop for a crop group (e.g. millet/wheat for cereals) and they have similar, but not equal monthly water demands (Supplement), a conservative approach is applied, whereby the larger figure for the crops have been applied, unless the difference between them is more than 40 mm, in which case this demand is reduced by 5 or 10 mm. The reason for applying the conservative approach is to ensure that the GWIP is not overestimated.

The irrigation efficiency (Irrig. Efficiency, Eq. 3) takes into consideration the water lost during the irrigation path from the water abstraction point to the water reaching the plants. Water losses occur mainly during water transport (i.e. pipe leakage or evaporation/leakage in open canal system) and in the field (i.e. water running off the surface or percolating past the root zone). Each irrigation cropping pattern zone has an irrigation efficiency coefficient based on figures found in the literature, type of crops irrigated and intensification level of the irrigation techniques (FAO, 1997) (Table 2). The coefficient is mainly based on surface water irrigation and it is here assumed applicable to GWI. This assumption implies a conservative estimate of GWIP as open canal water transport from rivers or lakes is typically found less efficient than groundwater, which is abstracted more locally and in a distributed fashion (Foster and Perry, 2010).

3.3 Other groundwater uses

Irrigation is only one of the groundwater uses and it is necessary to take into account the other anthropogenic and environmental groundwater uses. They are divided into four categories: domestic, industrial, and livestock demands as well as environmental requirements. Irrigation from groundwater is possible only after the groundwater demands of these uses have been satisfied.

Groundwater demand of anthropogenic activities is calculated for each cell using the density map of population and livestock from 2000 (FAO, 2007a, b) and data in Table 3.

Domestic, industrial and livestock water demand is assumed constant over the period 1960–2000.

The environmental groundwater requirement remains highly uncertain. To account for this, three scenarios have been applied: the environmental groundwater requirements represent 70 % (Scenario 1), 50 % (Scenario 2), and 30 % (Scenario 3) of the recharge, respectively over the continent (Pavelic et al., 2013).

4 Calculation of groundwater irrigation potential

The GWIP (Eq. 1) is calculated as the average annual value over the 1960–2000 period, using annual estimates of irrigation water demand (Irrig. Water Demand). Hence, a temporal average of the irrigation potential is obtained. However, rather than equally using the annual values of groundwater availability (GW Available), a constant averaged annual value of this parameter was used, rather than varying it between years. This in essence corresponds to smoothing out the variability in groundwater availability (and recharge) and accounting for the buffering effect of the resource. Hence, in low groundwater availability years, regular water availability is assumed. If the average GW Available is negative in a cell (due to persistent low recharge years or high human and environmental demand), the availability is set to zero for that cell.

For the Irrig. Water Demand (Eq. 3), annual values were processed from aggregated monthly data, using crop water demand and green water for the individual crop groups within each cell, accounting for the share of each crop group on the total crop group land (% of Area, Eq. 3). Since for each crop group, up to two specific crops can be grown in rotation on the same area but never concurrently (Supplement), the number of crops (n , Eq. 3) in this case refers to the number of crop groups, rather than specific crops. Similarly, the Crop Water Demand refers to the sum of the crop water demand of the actually grown crop in the crop group.

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5 Results

The average net irrigation water demand (Irrig. Water Demand \times Irrig. Efficiency) is shown in Fig. 4. It is seen (Fig. 4a) that the irrigation demand reflects primarily the density of cropland (Fig. 1) and the aridity of the regions (Fig. 4b).

The groundwater available for irrigation is the surplus recharge after satisfying human and environmental groundwater needs (Eq. 1). This varies according to the three scenarios (Fig. 5). The total renewable groundwater availability for irrigation across the continent ranges from 692 (Scenario 1) to 1644 km³ year⁻¹ (Scenario 3). Not surprisingly, the availability is greater along an equatorial band across the continent where rainfall and recharge are highest. It is also seen, that large parts of northern and southern Africa are devoid of excess recharge to enable irrigation from renewable groundwater resources.

Converting the groundwater availability into GWIP in terms of irrigable area, a similar pattern is found (Fig. 6). The white areas in central Africa with zero potential correspond to areas with no cropland, essentially areas covered by permanent forest. Appreciable hydrological potential exists for groundwater irrigation across much of Africa, except for the most arid regions and in the most southern part where demand from other sectors compete with GWI (data not shown). Hence, most regions in the Sahel and the eastern tract of the continent, from Ethiopia down to Zimbabwe, may provide significant unexplored opportunities for groundwater development for agriculture, with up to all cropland, and sometimes more, being irrigable from renewable groundwater. The maps also indicate that relatively large disparities in GWIP exist within individual countries, e.g. Ethiopia, Mozambique, Malawi and Zambia. Potential hotspot areas should be further explored in terms of other factors governing the potential for GWI development. Aggregating the GWIP across the continent, values range from 27.2×10^6 ha to 64.3×10^6 ha for the three scenarios, corresponding to 12.5 to 29.6% of the cropland. The GWIP for the 13 countries estimated by Pavelic et al. (2013) (13.5×10^6 ha) is here calculated to 12.8×10^6 ha, showing correspondence between the methods, though the

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artefact is discernible in the horn of Africa. Here, appreciable GWI exists (Fig. 7a), while Fig. 1 shows no cropland. The explanation could be that areas in this region are mostly irrigated pasture land, or pasture land converted into irrigated cropland after the 2000 map of cropland (Fig. 1) was produced.

6 Discussion

6.1 Uncertainty and variability of recharge and environmental requirements

In assessing the confidence of the methodology presented, the uncertainty and temporal variability of recharge as well as the uncertainty of the environmental requirements need to be taken into consideration. Table 4 summarizes estimations of groundwater recharge for a number of African countries from different sources. It shows that the annual recharge estimation from the hydrological model PCR-GLOBWB (this paper) is quite similar to the one estimated from the WaterGAP Global Hydrology Model (WGHM) (Döll and Fiedler, 2008) while there is more discrepancy with the FAO dataset. Since the GWIP is strongly dependent on the recharge, this uncertainty will be reflected in the GWIP.

The maps in Fig. 8 present the average annual recharge (Fig. 8a) and the coefficient of variation of the recharge (Fig. 8b) of the 41 year simulation period. The coefficient of variation shows clearly that the areas where the recharge is smaller (say less than 50 mm per year) also have the highest variability over the years. In these areas, recharge can vary from zero to double of the average recharge (dark red colour). The results indicate that where groundwater recharge is sufficient to support GWI in these areas, it is likely to be a very strategic resource in buffering seasonal and inter-annual climate variability. Secondly, the actual buffering capacity of groundwater, which is governed by the longer-term storage capacity of the aquifers, more so than the recharge, becomes equally important in these areas and need to be addressed in further and more detailed assessments. In the present approach, buffering of the groundwater is

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This could significantly increase the food production and productivity in the region from a reliable and renewable resource.

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Table 1. Areal proportion of crop groups cultivated in Africa for the year 2000, adapted from Monfreda et al. (2008).

Crop group	Area (10 ⁶ ha)	Proportion (%)
Cereals	79.4	47.92
Oils	19.6	11.83
Roots	17.8	10.74
Pulses	16.3	9.84
Vegetables	4.4	2.66
Sugar crops	1.4	0.84
Fruit	8.4	5.07
Forage	3.7	2.23
Fiber	4.2	2.53
Tree nuts	1.3	0.78
Other crops	9.2	5.56
Total	165.7	100 %

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Table 2. Irrigation efficiency dependent on irrigation cropping pattern zone (FAO, 1997).

Irrigation cropping pattern zone number	Zone name	Irrigation efficiency (%)
1	Mediterranean coastal zone	60
2	Sahara oases	70
3	Semi-arid to arid savanna West–East Africa	50
4	Semi-arid/arid savanna East Africa	50
5	Niger/Senegal rivers	45
6	Gulf of Guinea	50
7	Southern Sudan	50
8	Madagascar tropical lowland	50
9	Madagascar highland	50
10	Egyptian Nile and Delta	80
11	Ethiopian highlands	50
12	Sudanese Nile area	80
13	Shebelli-Juba river area in Somalia	50
14	Rwanda – Burundi – Southern Uganda highland	50
15	Southern Kenya – Northern Tanzania	50
16	Malawi – Mozambique – Southern Tanzania	45
17	West and Central African humid areas	45
18	Central African humid areas below equator	45
19	Rivers effluents on Angola/Namibia/Botswana border	50
20	South Africa – Namibia – Botswana desert and steppe	65
21	Zimbabwe highland	60
22	South Africa – Lesotho – Swaziland	60
23	Awash river area	50

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Uses/unit		Daily water need (L)	Portion assumed to come from groundwater (%)
Domestic	Inhabitant	50	75
Industrial	Inhabitant	25	75
Livestock	Big ruminant	40	100
	Small ruminant	20	100
	Pig	30	100
	Poultry	0.2	100

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Table 4. Comparison of estimations of groundwater recharge for selected African countries.

Country	Recharge (mm year ⁻¹)		
	FAO, AQUAStat (2009) ^a	Döll and Fiedler (2008) ^b	This paper ^c
Burkina Faso	34.6	39	39
Ethiopia	18.1	39	80
Ghana	110.3	105	127
Kenya	6.0	46	29
Malawi	21.1	164	170
Mali	16.1	22	23
Mozambique	21.3	104	82
Niger	2.0	12	4
Nigeria	94.2	163	154
Rwanda	265.8	68	78
Tanzania	31.7	93	90
Uganda	122.9	95	50
Zambia	62.4	108	117

^a <http://www.fao.org/nr/water/aquastat/main/index.stm> (last access: 2 April 2014).

^b Data as provided in Margat and Gun (2013).

^c Data calculated from the PCR-GLOBWB model (Van Beek et al., 2011).

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Scenario 1			Scenario 2			Scenario 3		
Min.*	Average	Max.*	Min.	Average	Max.	Min.	Average	Max.
442.2	692.1	990.1	751.1	1168.3	1664.9	1006.1	1644.5	2339.7

* Min. and Max. refers to minimum and maximum annual values over the 41 years.

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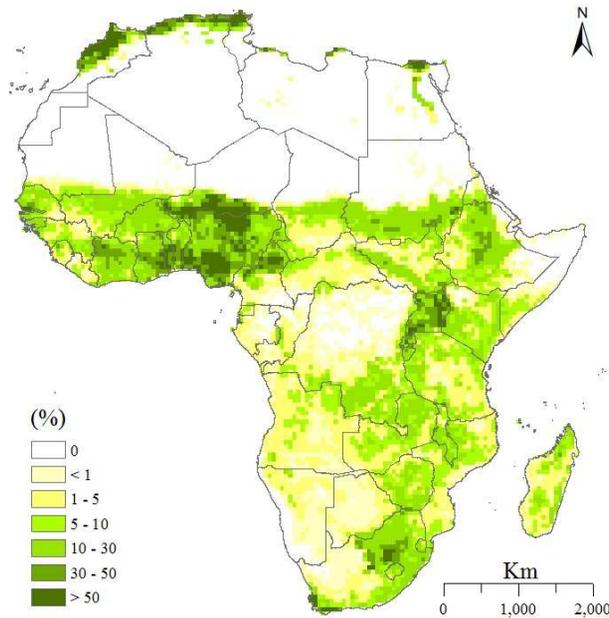


Figure 1. Proportion of cropland per cell ($0.5^\circ \times 0.5^\circ$) in 2000 (Ramankutty et al., 2008).

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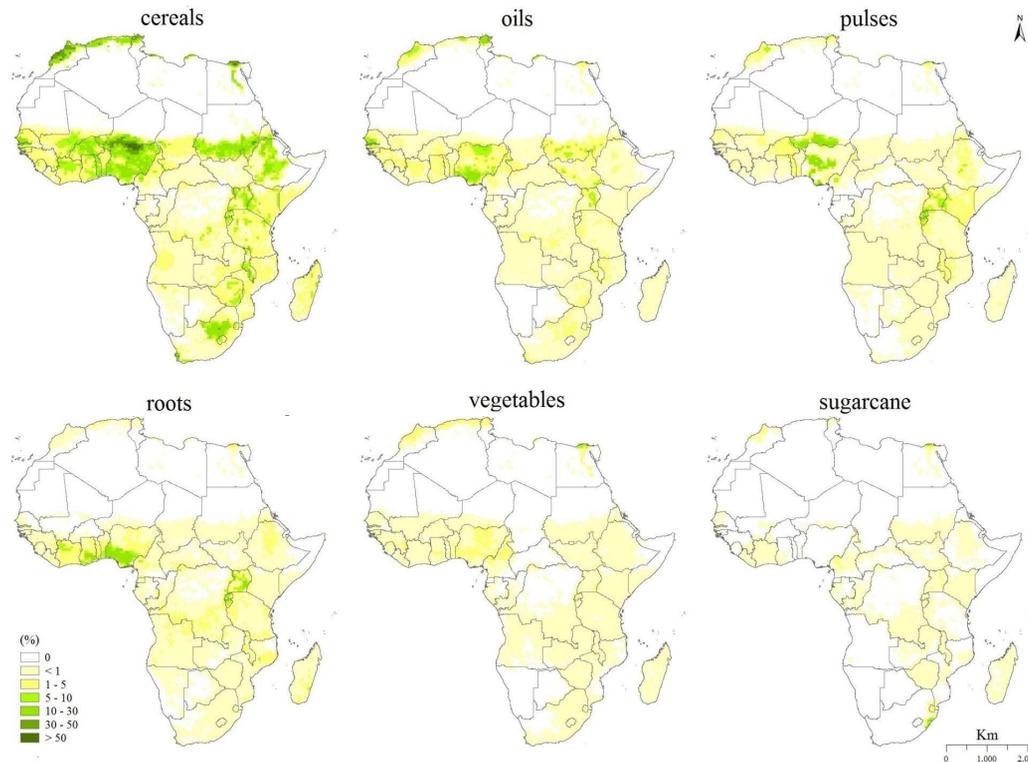


Figure 2. Proportion of crop group area per cell ($0.5^\circ \times 0.5^\circ$) cultivated in 2000 of the six largest crop groups (adapted from Ramankutty et al., 2008).

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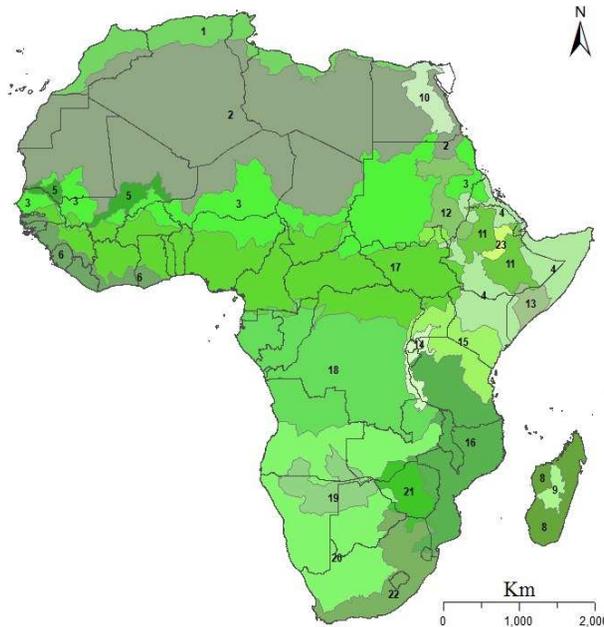


Figure 3. Delineation of the 23 irrigation cropping pattern zones in Africa (based on FAO, 1997).⁴

⁴<http://www.fao.org/geonetwork/srv/en/main.home> (last access: 1 April 2014)

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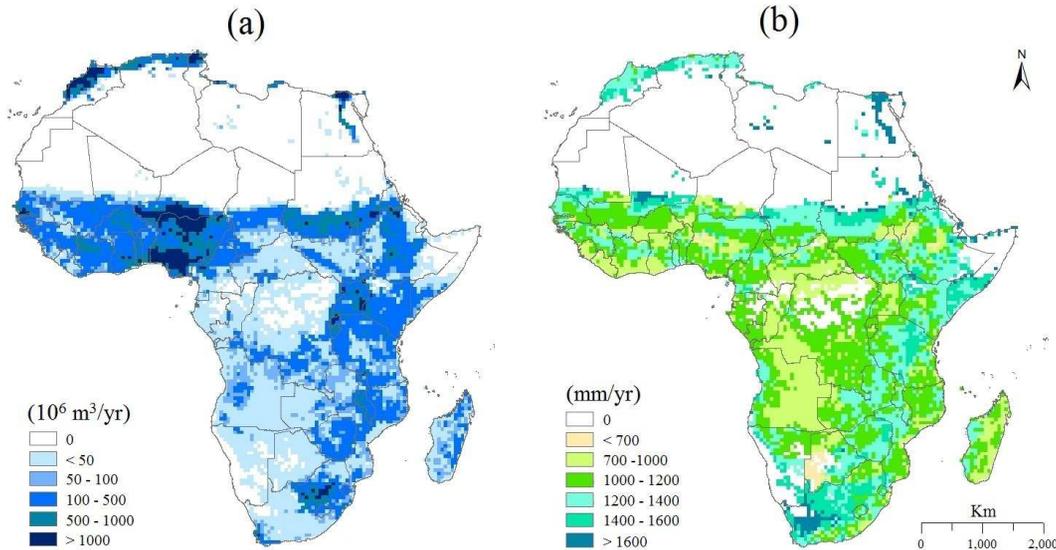


Figure 4. Estimated average net irrigation water demand (1960–2000) for the irrigated cropland **(a)** expressed in $\text{mill. m}^3 \text{ year}^{-1} \text{ cell}^{-1}$ ($0.5^\circ \times 0.5^\circ$), and **(b)** in mm year^{-1} .

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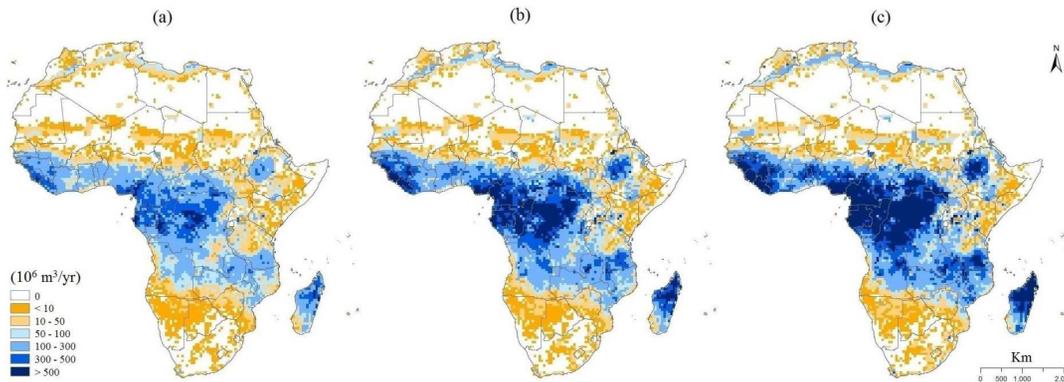


Figure 5. Average groundwater availability for irrigation (1960–2000), expressed in $\text{mill. m}^3 \text{ year}^{-1} \text{ cell}^{-1}$ ($0.5^\circ \times 0.5^\circ$), for various levels of environmental groundwater requirements as a fraction of recharge, **(a)** scenario 1: 70 %, **(b)** scenario 2: 50 %, **(c)** scenario 3: 30 %.

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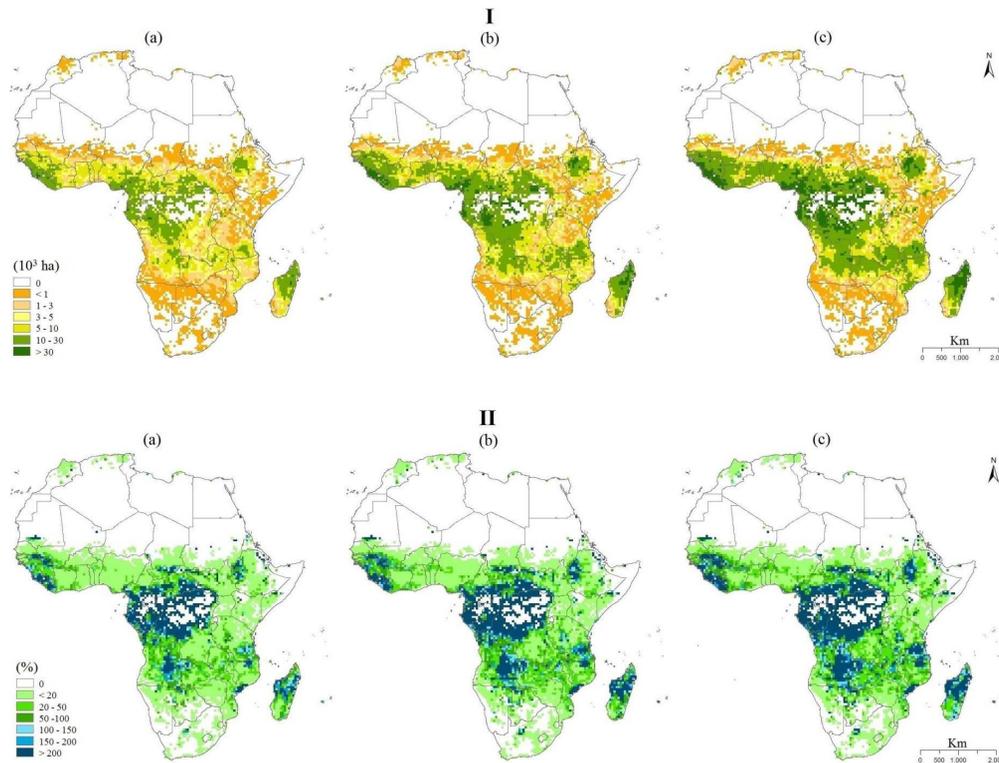


Figure 6. (I) Total area in 10^3 ha irrigable with groundwater inside a cell ($0.5^\circ \times 0.5^\circ$), and (II) proportion of cropland irrigable with groundwater, for various levels of environmental groundwater requirements as a fraction of recharge, (a) scenario 1: 70 %, (b) scenario 2: 50 %, (c) scenario 3: 30 %.

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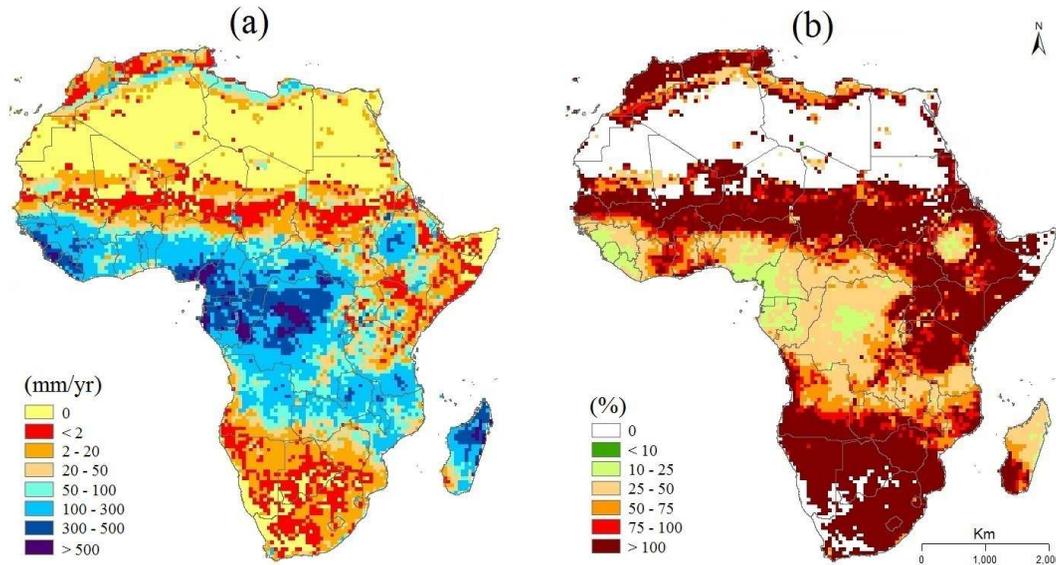
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Figure 8. (a) Average annual recharge (mm year^{-1}), and (b) its coefficient of variation (%), both over the period 1960–2000 (data from Van Beek et al., 2011).

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