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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 km^3 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 development[1] 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 GIDA[2], 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

[1] Definition 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.

[2] In the Ghana National Irrigation Policy, groundwater irrigation falls under the category "informal irrigation".

lack of knowledge of the resource and best options for sustainable development. So while present levels of development are comparatively low and most development occurs in the informal sector (Villholth, 2013), progress towards greater and long-term benefits need to be informed by estimations of upper limits for sustainable development and most appropriate geographic areas for development. The need for qualified estimates of groundwater irrigation potential (GWIP) is recognized at the national (MoFA and GIDA, 2011; Awulachew et al., 2010) as well as regional scale (MacDonald et al., 2012). Qualitative, relative groundwater potential was mapped for Ethiopia by MacDonald et al. (2001), however, with no specific focus on the potential for irrigation. You et al. (2010) estimated the potential contribution from small-scale irrigation (incl. ponds, small reservoirs, rainwater harvesting, and groundwater) in Africa to be 0.3 to 16×10^6 ha based on a distributed multi-criteria analysis. Pavelic et al. (2012, 2013) afforded a relatively simple water balance approach to provide country or catchment scale estimates of gross GWIP in terms of irrigable cropland, taking into consideration the crop irrigation water needs and disregarding existing irrigation development. Water available for irrigation was constrained by renewable groundwater resources, priority demands from domestic, livestock, industrial uses as well as environmental requirements. They determined the GWIP of 13 semi-arid countries in SSA to be in the range of $13.5 \pm 6.0 \times 10^6$ ha, or between $0.1–3.9 \times 10^6$ ha per country. While the previous estimations of GWIP in Africa were continental (You et al., 2010), national (Pavelic et al., 2013), or sub-national (Pavelic et al., 2012) in scope, the present paper builds on the latter approach providing a fully distributed and consistent assessment of the gross GWIP for the entire continent at a grid scale of 0.5°. By doing so, regional differences across the continent become conspicuous and variability within the countries also becomes apparent. The extent and distribution of GWIP is subsequently compared with the existing GWI extent and distribution across Africa to determine net GWIP, i.e. areas and regions with high and low residual GWIP. Finally, the limitations and uncertainties related to the methodology are assessed and discussed.

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:

$$\text{GWIP} = \frac{\text{GW Available}}{\text{Irrig. Water Demand}} \tag{1}$$

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

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

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:

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

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

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 calendar[3] 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.

5 Results

The average net irrigation water demand (Irrig. Water Demand × 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 km^3 $year^{-1}$ (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

present method does indicate the distributed extent of GWIP across the countries and for the whole continent. In Appendix A (Table A1), the GWIP for the individual countries in Africa are given. The results show that the GWI area in Africa can safely be expanded by a factor of 10 or more, based on the conservative renewability and environmental requirements of the resource and the present human demands, possibly with wide livelihood benefits for smallholder farmers in many Sahel and semi-arid regions of eastern Africa. Some blue areas with very high potential relative to the cropland area (Fig. 6i), as seen in arid parts of South Africa, Mali and Sudan can be explained by very small cropland areas relative to the cell size. Hence, accumulated recharge over the cell, albeit low in nominal terms, may be sufficient to irrigate these areas.

In order to further analyse the GWIP, and explore the untapped part of the potential, the results are compared with existing data on the present development of GWI across Africa (Fig. 7). The map in Fig. 7a presents the best available continent-wide data for areas equipped for GWI (Siebert et al., 2010), while Fig. 7b shows the relative GWIP (in terms of area) in Scenario 2 (the environmental groundwater requirements represent 50 % of recharge), expressed as the percentage of the data from Siebert. While this approach only captures and compares areas having non-negative values for present GWI development, it gives a clear indication of the contrast across the continent with respect to the areas with and without further GWIP (the yellow and green areas vs. the red areas). In northern and southern Africa the untapped development potential is very limited or patchy, while in western Africa and the eastern belt, still appreciable GWI development potential exists. These results also indicate, that presently GWI is mostly developed in regions with limited potential, and significantly in areas where groundwater is non-renewable (like in northern Africa) or where little uncommitted renewable groundwater resources exist. In fact, the method also gave indications of where groundwater is already over-allocated, based only on the human needs (let alone irrigation and the environment) relative to the recharge. This is generally not the case, but occurrences appear in arid high-density livestock or populated parts of north-eastern South Africa and south-eastern North Sudan (data not shown). An apparent 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

only considered by using the long-term average GW Available in Eq. (1), as explained in the Sect. 4. Similarly, the buffering capacity of groundwater in a spatial sense was applied in assuming that all recharge in a cell can be captured anywhere in that cell.

The uncertainty associated with the environmental requirements relates to the lack of knowledge of the location and functioning of ecosystems dependent on groundwater throughout Africa and their groundwater requirements in quantitative terms. Such ecosystems and their requirements may depend on the hydrogeological setup of an area, the scale of the aquifers, and the climate (Tomlinson, 2011). However, in absence of better understanding and tested approaches, the three scenarios approach was used (Pavelic et al., 2013). When comparing the uncertainty related to the scenarios in terms of the GW Available (Table 5) (about 480 km^3 $year^{-1}$, as calculated from the difference between the averages of Scenario 2 and 1, and Scenario 2 and 3, respectively), and the uncertainty related to the recharge (estimated from the range between the average and min. and average and max. annual GW Available for Scenario 2, which is 417 and 496 km^3) it is apparent that the uncertainty on groundwater availability related to the environmental requirements is on the same order of magnitude as the effect of the temporal variability of recharge.

6.2 Limitations of approach

The water balance approach considers renewable water availability as the major controlling parameter for GWIP and assumes non-limiting conditions in terms of other fundamental physical properties, e.g. soil and water quality, terrain slope, and groundwater accessibility (as determined by e.g. depth of the usable aquifer, storage available for recharge, and well yields) for the implementation of GWI. Considering an average landholding size of 1 ha with a single well, or alternatively 1 well per ha for landholdings larger than 1 ha, over the continent and the gross irrigation water demand per year varying between 470 and 3887 mm per year, with the cropping pattern applied in the present study, an average cropping season of 240 days of daily irrigation for 8 h, this translates into a required well yield varying from 0.65 to 5.6 L s^{-1}. Comparing this with continental-wide maps of well yields (MacDonald et al., 2012), it is evident that in certain geological formations, like the basement rock aquifers, that occupy 34 % of the continent (Adelana and MacDonald, 2008), the yield of the geological substrata may in places be limiting for larger scale or very intensive GWI development.

Possible constraints related to hydrogeology as well as water quality and socio-economic constraints, such as infrastructure (roads, markets, energy/electricity) may further reduce this potential or hamper its realization as will be further analysed in a companion paper.

Furthermore, climate trends and progressive water demands from growing human and livestock populations have not been considered. For these reasons, it is suggested to apply the most conservative estimates (i.e. Scenario 1) for a robust estimate of hydrological GWIP.

7 Conclusions

The present study has estimated the extent and distribution of groundwater irrigation potential (GWIP) across the African continent (0.5° resolution), based on the hydrologically available and renewable groundwater over a 41 year recent historic period and using crop and cropland data from the beginning of the century. The GWIP is assessed to be between 27.2×10^6 ha and 64.3×10^6 ha, depending on the proportion of recharge assumed allocated preferentially to the environment (30–70 %), while assuming constant human needs for groundwater. This is a gross estimate, disregarding existing groundwater irrigation (GWI). However, with the present GWI area amounting to approximately 2×10^6 ha, the difference between net and gross potential is small. However, comparing GWIP to existing maps of GWI, it is clear, that present GWI has been primarily developed in northern and southern Africa where the development potential is relatively limited, and where it is governed by abstraction from non-renewable or already stressed resources, while the rest of the continent (except for the Sahara region) still has appreciable potential, especially for smallholder and less intensive GWI.

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

Table 3. Other groundwater uses (adapted from Pavelic et al., 2013).

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).

Table 5. Aggregated groundwater available (km^3 year^{-1}) for the three environmental scenarios.

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.

Table A1. Gross groundwater irrigation potential per country in Africa.

Countries	Area of cropland irrigable with groundwater* (10^3 ha) Scenario (Percentage of groundwater going to environment) 1 (30 %)	2 (50 %)	3 (70 %)
Algeria	87	58	30
Angola	4458	3180	1901
Benin	454	323	191
Botswana	68	48	28
Burkina Faso	330	232	133
Burundi	124	86	49
Cameroon	3484	2483	1483
Central African Republic	4141	2956	1771
Chad	602	427	252
Côte d'Ivoire	1781	1267	754
Democratic Republic of Congo	12 443	8876	5309
Djibouti	3	2	1
Egypt	2	1	1
Equatorial Guinea	280	200	120
Eritrea	11	7	4
Ethiopia	3161	2233	1306
Gabon	2279	1628	976
Gambia	28	20	11
Ghana	930	659	388
Guinea	2011	1434	857
Guinea-Bissau	166	118	71
Kenya	447	310	173
Lesotho	12	8	5
Liberia	1272	908	544
Libya	21	15	8
Madagascar	4871	3473	2075
Malawi	511	363	214
Mali	784	556	329
Mauritania	61	43	26
Morocco	115	77	40
Mozambique	1764	1256	748
Namibia	94	67	39
Niger	32	20	10
Nigeria	4281	3023	1766
Republic of Congo	2918	2082	1246
Rwanda	73	50	28
Senegal	417	295	174
Sierra Leone	1298	926	554
Somalia	60	42	24
South Africa	181	120	63
South Sudan	1453	1033	613
Sudan	431	300	170
Swaziland	14	10	6
Tanzania	2390	1696	1003
Togo	269	191	113
Tunisia	19	13	6
Uganda	440	308	175
Western Sahara	0	0	0
Zambia	2976	2122	1268
Zimbabwe	301	211	121

* Errors up to 35 % for small countries (due to the cell size, the projection used in GIS and the shape of the countries i.e. Gambia).

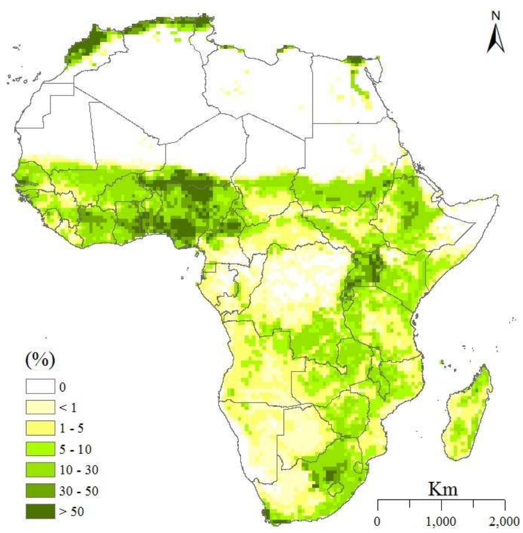

Figure 1. Proportion of cropland per cell (0.5° × 0.5°) in 2000 (Ramankutty et al., 2008).

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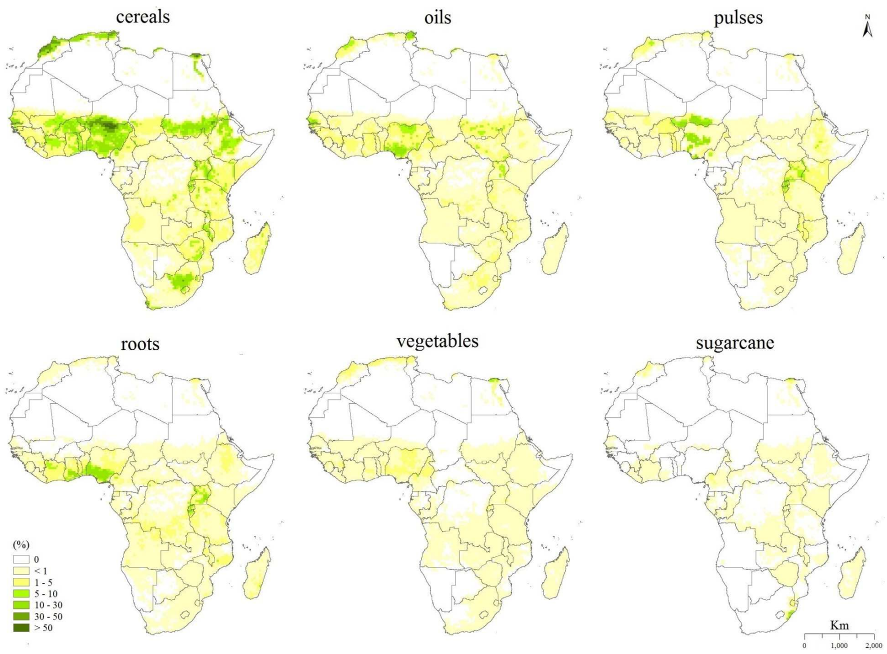

Figure 2. Proportion of crop group area per cell (0.5° × 0.5°) cultivated in 2000 of the six largest crop groups (adapted from Ramankutty et al., 2008).

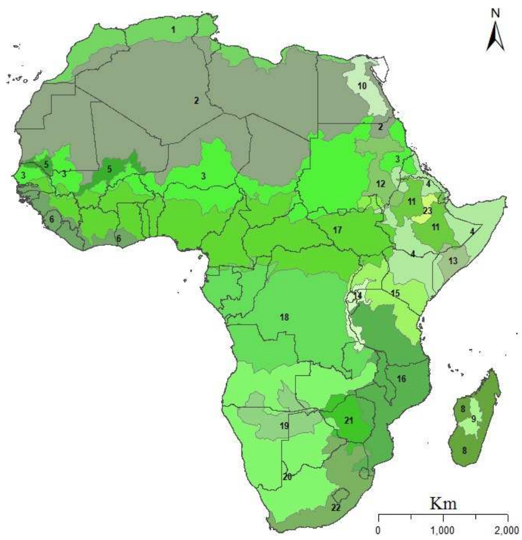

Figure 3. Delineation of the 23 irrigation cropping pattern zones in Africa (based on FAO, 1997).[4]

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

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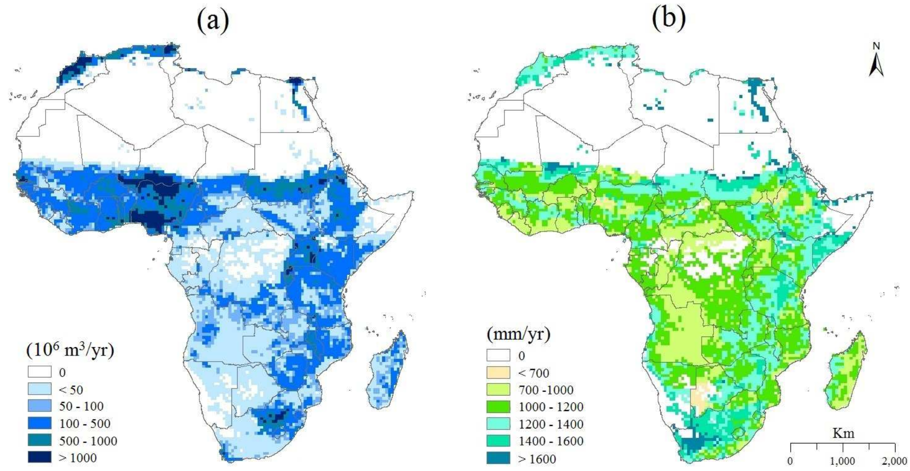

Figure 4. Estimated average net irrigation water demand (1960–2000) for the irrigated cropland **(a)** expressed in mill. m^3 $year^{-1}$ $cell^{-1}$ ($0.5^{\circ} \times 0.5^{\circ}$), and **(b)** in mm $year^{-1}$.

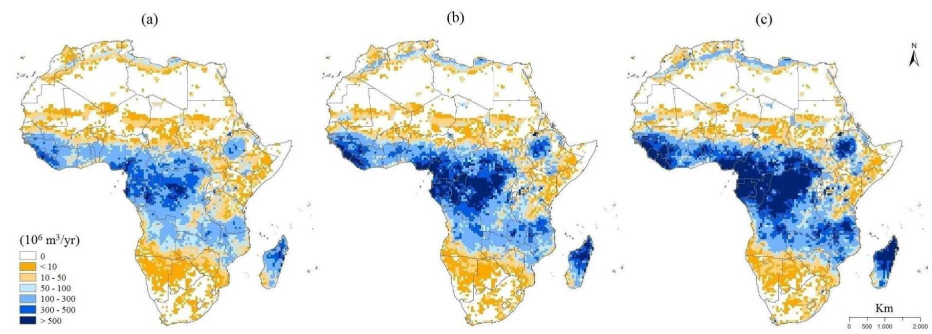

Figure 5. Average groundwater availability for irrigation (1960–2000), expressed in mill. m^3 $year^{-1}$ $cell^{-1}$ ($0.5^{\circ} \times 0.5^{\circ}$), for various levels of environmental groundwater requirements as a fraction of recharge, **(a)** scenario 1: 70 %, **(b)** scenario 2: 50 %, **(c)**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

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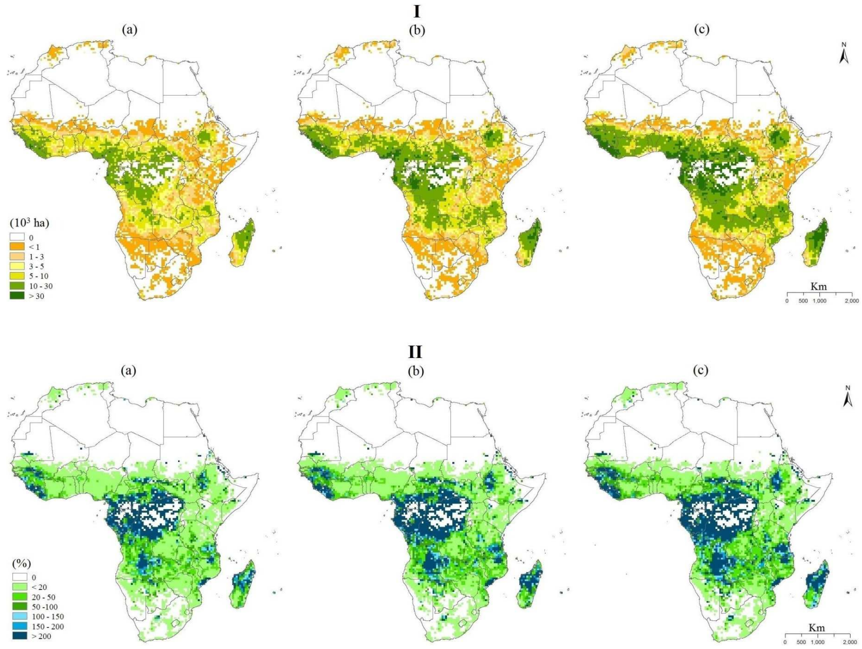

Figure 6. (I) Total area in 10^3 ha irrigable with groundwater inside a cell (0.5° × 0.5°), and (II) proportion of cropland irrigable with groundwater, for various levels of environmental groundwater requirements as a fraction of recharge, **(a)** scenario 1: 70 %, **(b)** scenario 2: 50 %, **(c)** scenario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

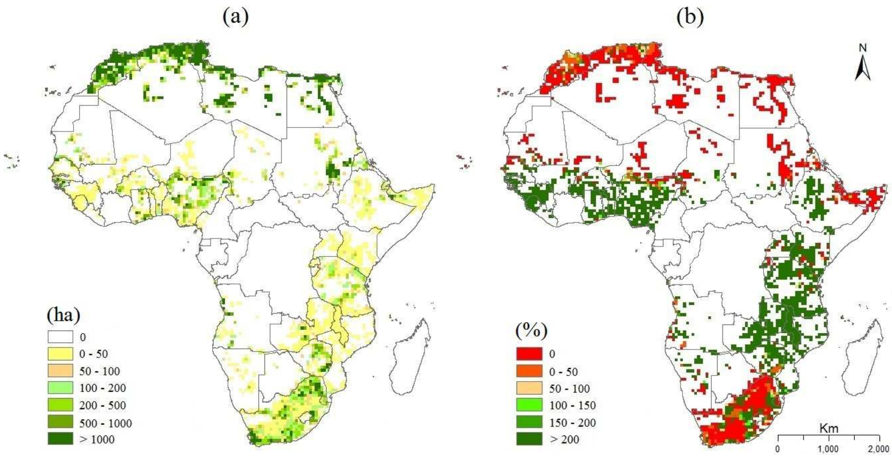

Figure 7. (a) Area irrigated with groundwater in 2005 expressed in ha per cell, adapted from Siebert et al. (2013), and **(b)** groundwater irrigation potential for scenario 2 (the environmental groundwater requirements represent 50 % of the recharge) for the year 2000, expressed as the percentage of the area irrigated with groundwater in 2005.

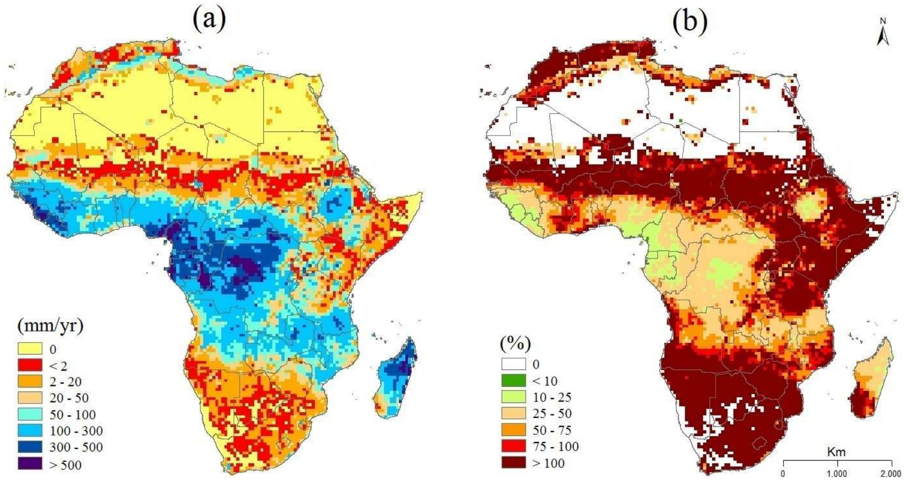

Figure 8. (a) Average annual recharge (mm year^{-1}), and **(b)** its coefficient of variation (%), both over the period 1960–2000 (data from Van Beek et al., 2011).