Sorbonne Université

Ecole doctorale

Géosciences, Ressources Naturelles et Environnement

Mapping sustainable irrigation development potential with renewable groundwater in Africa for reducing African food insecurity

Par Yvan Altchenko

Thèse de doctorat en géosciences environnementales

Dirigée par Agnès Ducharne et Karen Villholth

Présentée et soutenue publiquement le 14 Décembre 2018

Devant un jury composé de :
Agnès Ducharne, HDR, DR CNRS, METIS, Sorbonne Université (Directrice de thèse)
Karen Villholth, Sub-team leader, IWMI (Co-directrice de thèse)
Alain Vidal, HDR, Director of Partnership, Food and Water, WBCSD (Rapporteur)
Thierry Pellarin, HDR, DR CNRS, UGA-IGE (Rapporteur)
Valérie Plagnes, HDR, Professeur à METIS, Sorbonne Université (Examinateur)
Thierry Lebel, HDR, DR IRD, UGA-IGE (Examinateur)

Except where otherwise noted, this work is licensed under
http://creativecommons.org/licenses/by-nc-nd/3.0/

To Mia, Sasha, Stuart, Rollande and Nicolas

Remerciements

Mes remerciements vont tout d'abord à Agnès Ducharne pour m'avoir fait confiance en acceptant de me diriger et pour m'avoir soutenu lors de la prolongation en quatrième année. Son soutien et ses commentaires tout au long de ce travail m'ont permis de me questionner et de progresser. J'espère que ce manuscrit sera le niveau de son attente. I am also extremely grateful to Karen Villholth from IWMI who accepted to be co-director while I was already working under her supervision. I learnt and grew a lot as a scientist over the five years working together. My experience at IMWI has been the most amazing working experience from a working point of view but also from a personal and cultural point of view.

Je souhaite également remercier mon employeur, le Ministère de l'Agriculture et de l'Alimentation, qui m'a donné l'opportunité de travail au sein de l'IWMI à Prétoria (Afrique du Sud) pendant six ans. Sans cette aventure, cette dissertation n'existerait pas. Je remercie Dominique Rollin de G-EAU (IRSTEA) qui a implanté la graine du doctorat dans mon cerveau. Il m'a fallu un peu de temps pour la faire germer mais j'espère que cette thèse est la preuve qu'elle a bien poussé. Je n'oublie pas de remercier non plus les autres membres de G-EAU que j'ai pu côtoyer. Je pense notamment à Olivier Barreteau, Sami Bouarfa ou Sylvie Morardet.

Je remercie également les membres du jury pour avoir accepté d'évaluer mon travail, pour leur expertise et conseil. Je tiens à remercier particulièrement les membres du comité de thèse et plus spécialement Pierre Ribstein de METIS et Sami Bouarfa qui n'ont pas pu être membres du jury mais qui ont suivi ce travail et apporté de judicieux commentaires.

Je voudrais également remercier le projet ANR IGEM (Impact of Groundwater in Earth system Models, N° ANR-14-CE01-0018-04) pour son soutien.

Finalement, cette dissertation n'aurait pas été possible sans le support et la compréhension des personnes que j'aime et qui m'aiment. Merci Papa et Maman pour votre soutien constant, quoi qu'il puisse arriver. Thanks to Stuart who has been supportive and loving in all kind of way. Thanks to Amy and Molly who stepped up from step-daughter to full time nanny anytime it was necessary. And finally, thanks to my babies, Mia and Sasha, for making my life full of love and meaningful even if you didn't make easy this thesis.

Résumé

La population de l'Afrique devrait doubler entre 2015 et 2050, mais les efforts actuels pour réduire la prévalence de la sous-alimentation africaine sont inférieurs à ceux observés dans d'autres parties du monde (DESA, 2015). En fait, l'Afrique n'a pas réussi à atteindre l'Objectif de Développement du Millénaire de réduction de 50% de sa population souffrant de la faim entre 1990 et 2015. Les objectifs africains visant à éliminer la faim d'ici 2030 et à assurer des systèmes de production alimentaire durables pour accroître la productivité et la production sont désormais les objectifs à atteindre (Objectifs de Développement Durable 2.1 et 2.4). Dans le contexte de la croissance démographique, de l'éradication de la faim et de l'incertitude de l'impact du changement climatique sur les précipitations en Afrique (Niang et al., 2014), il est nécessaire d'augmenter significativement la production alimentaire, en particulier la production des cultures, qui représente environ 89% du régime alimentaire africain (Alexandros et Bruinsma, 2012). L'augmentation du rendement des cultures est une composante essentielle de l'augmentation de la production alimentaire, car l'expansion des terres cultivées est limitée dans la plupart des pays (Jayne et al., 2014).

L'irrigation est généralement considérée comme un outil pour augmenter le rendement des cultures, en grande partie parce qu'elle a largement contribué à la « révolution verte » en Asie, où le rendement des cultures a augmenté de plus de 75% entre 1961 et 2007 (Alexandros et Bruinsma, 2012). Cependant, la superficie équipée pour l'irrigation en Afrique s'est développée à un rythme lent depuis 1950. Le développement de l'irrigation doit s'accélérer pour répondre à la demande d'une population en expansion et pour atténuer la faim, en particulier en Afrique subsaharienne (Siebert et al., 2015). De plus, les eaux souterraines ont été négligées en tant que sources d'eau pour l'irrigation et ne sont utilisées que dans 18,5% des zones équipées en irrigation en Afrique alors qu'elles alimentent 38% des zones équipées en irrigation en Asie (Siebert et al, 2010). Pourtant, les eaux souterraines sont reconnues comme étant une source en eau sûre, fiable (surtout pendant les sécheresses) et abordable (Calow et al., 1997; Calow et al., 2010). De plus, le rendement des cultures provenant de l'irrigation des eaux souterraines est généralement supérieur à celui de l'irrigation des eaux de surface (Burke et al., 1999). Il semble également que les eaux souterraines existent en quantité sur une grande partie du continent, même si elles ne sont pas toutes disponibles pour l'extraction ou distribuées de manière

uniforme (MacDonald et al., 2012). Cependant, les zones qui peuvent être développées avec l'irrigation par les eaux souterraines n'ont pas été identifiées sur le continent, soulevant la question: *en Afrique, existe-t-il un potentiel pour augmenter les surfaces de cultures irriguées avec les eaux souterraines renouvelables ?*

Cette thèse aide à répondre à cette question et est divisée en cinq chapitres. Après la contextualisation de l'irrigation agricole à partir des eaux souterraines en Afrique dans le **chapitre un** et une analyse de l'état des connaissances scientifiques dans le **chapitre deux**, la thèse propose deux approches différentes mais complémentaires pour estimer le potentiel de développement de l'irrigation agricole par les eaux souterraines en Afrique : une approche quantitative et hydrologique et une approche contextuelle.

Le **chapitre trois** répond à la question: *quelle superficie de cultures en Afrique, et où, peuvent être irriguées à partir des eaux souterraines renouvelable ?* Pour cela, on estime l'étendue et la répartition du potentiel d'irrigation agricole par les eaux souterraines renouvelables sur le continent africain à une résolution de 0,5 degré (environ 50 km sur 50 km) à partir du bilan hydrique uniquement. Il s'agit de l'approche quantitative et hydrologique de ce potentiel qui est appelé potentiel de la ressource en eau souterraine pour l'irrigation agricole (Groundwater Irrigation Resource Potential ou GIRP). L'analyse à l'échelle du continent examine la disponibilité des eaux souterraines renouvelables pour l'irrigation agricole durable en tenant compte des conditions climatiques à long terme, et des besoins en irrigation des cultures existantes. Elle définit la ressource en eaux souterraines pour l'irrigation comme la fraction de la recharge des eaux souterraines restantes après satisfaction des besoins humains et environnementaux actuels. En raison de l'incertitude considérable des besoins environnementaux en eau souterraine, trois scénarios ont été considérés, laissant 30%, 50% et 70% de la recharge pour l'environnement. L'étude a regroupé les cultures dominantes en six groupes (céréales, légumineuses, racines, huiles, légumes et canne à sucre) et tient compte des rotations culturales et des conditions climatiques pour estimer les besoins d'irrigation correspondants, c'est-à-dire l'eau supplémentaire nécessaire pour atteindre la croissance optimale des cultures après absorption par les cultures de l'eau naturellement disponible dans le sol via les pluies. L'étude convertit donc l'excédent de la fraction de la recharge des eaux souterraines en terres cultivables potentiellement irrigables en appliquant une approche zonale.

Les résultats cartographient l’étendue du potentiel des eaux souterraines pour l’irrigation agricole sur le continent Africain et montrent que jusqu'à 105,3 millions d’hectares de terres cultivées peuvent être irrigués avec de la nappe phréatique, selon les trois scénarios et sans tenir compte de l'irrigation existante. Le scénario le plus conservateur (70% de la recharge revient dans l'environnement, ce qui signifie qu'une partie des 30% restant sera disponible pour l'irrigation après avoir satisfait tous les autres besoins tels que l'approvisionnement en eau potable, les besoins industriels et l'abreuvement du bétail) correspond au GIRP et indique que 44.6 millions d’hectare de terres cultivables peuvent être durablement irrigués avec des eaux souterraines (carte du GIRP). Si le développement actuel de l'irrigation par les eaux souterraines est principalement situé en Afrique du Nord et en Afrique australe, où le potentiel durable est limité ou épuisé, il existe un potentiel inexploité en Afrique de l'Est et dans la région du Sahel qui pourrait améliorer considérablement la sécurité alimentaire en Afrique.

L’approche quantitative et hydrologique du potentiel ne prend pas en compte les facteurs moteurs du développement de l'irrigation par les eaux souterraines, à l'exception de la quantité d'eau souterraine et du besoin en eau des cultures.

Le **chapitre quatre** essaie d’intégrer ces autres facteurs biophysiques et socio-économiques pour affiner l’estimation du potentiel des eaux souterraines renouvelable pour l’irrigation agricole. Il répond à la question : *quelle superficie de cultures en Afrique, et où, mérite d’être développée avec de l’irrigation à partir des eaux souterraines renouvelables* ? L’analyse à l’échelle du continent africain et à une résolution de 0,005 degré (environ 0.5 km sur 0.5 km) vise premièrement à cartographier les zones, à l’intérieur des pays, qui sont plus ou moins propices au développement de l’irrigation agricole durable avec les eaux souterraines, puis deuxièmement à redistribuer le potentiel déterminé dans le chapitre trois (GIRP) sur les zones qui méritent le plus d’être développées avec de l’irrigation agricole durable à partir des eaux souterraines.

La première partie du chapitre quatre correspond donc à l’approche contextuelle du potentiel d'irrigation agricole durable par les eaux souterraines, appelée moteur du développement de l’irrigation agricole durable par les eaux souterraines (Groundwater

Irrigation Development Driver ou GIDD). L'analyse identifie les facteurs moteurs du développement de l'irrigation agricole à partir des eaux souterraines. Les six facteurs moteurs du développement retenus pour l'étude sont la disponibilité des eaux souterraines renouvelables, les besoins en eaux des cultures, l'accès aux eaux de surface, l'accès au marché, l'adéquation du terrain à l'agriculture, et l'investissement dans les forages. Chaque facteur est cartographié à l'échelle continentale (carte individuelle de GIDD) et hiérarchisé en cinq classes de contribution au développement de l'irrigation durable par les eaux souterraines (extrêmement, fortement, modérément, légèrement et non-propice). L'analyse agrège ensuite les cartes individuelles par le biais d'une analyse cartographique composite multicritère en utilisant différentes méthodes de pondération puis en retenant la classe de contribution la moins élevée afin de déterminer les zones propices au développement de l'irrigation (carte de GIDD). Les résultats montrent que les zones dans lesquelles le développement de l'irrigation par les eaux souterraines pourrait être développé se situent le long d'une bande ouest-est allant du Sénégal et de la Guinée à l'Ethiopie et d'une large bande nord-sud-ouest allant de l'Ethiopie au Zimbabwe et l'Angola. La plupart des cellules sont très à légèrement propices au développement de l'irrigation avec les eaux souterraines. Les zones extrêmement et très propices se trouvent en particulier le long du Sahel, du sud de la Somalie et de l'Afrique du Sud. Les zones non favorables se trouvent principalement dans des poches à la frontière entre le Tchad et la RCA, dans les hauts plateaux éthiopiens et à la frontière avec l'Angola, le Botswana et la Namibie.

La seconde partie du chapitre quatre cartographie et quantifie le potentiel de développement durable de l'irrigation des eaux souterraines (Groundwater Irrigation Development Potential ou GIDP). Cela correspond aux zones du GIRP qui sont les plus propices au développement de l'irrigation des eaux souterraines. Les résultats estiment qu'en Afrique, 19,3 millions d'hectares mériteraient d'être développés avec de l'irrigation agricole durable à partir des eaux souterraines. Cela représente une multiplication par quatre des surfaces par rapport à l'irrigation existante à partir des eaux souterraines en Afrique et par soixante-quinze, si l'on exclut la région du Maghreb et l'Afrique du Sud, où le GIDP est déjà épuisé. Les plus grandes surfaces de GIDP sont principalement situées le long de la ligne ouest-est de l'Angola au nord du Mozambique et au sud du Sahel. Les régions semi-arides du Sahel et de l'Afrique de l'Est ont un potentiel de développement plus limité mais cela pourrait améliorer considérablement la sécurité alimentaire en Afrique, spécialement pour les petits fermiers. Les tests d'incertitude sur les résultats montrent que la disponibilité des eaux souterraines et les besoins en eau des cultures sont les facteurs dominants. Les résultats, hors zones sèches, pourraient être surestimés mais les calculs sont fiables dans les zones arides (Sahel, Corne de l'Afrique et Afrique australe).

Enfin, dans le **chapitre cinq**, la thèse conclut qu'en Afrique, il existe donc un potentiel conséquent pour développer davantage l'irrigation durable des cultures à partir des eaux souterraines. Ce potentiel est présent en dehors des zones arides et équatoriales. Il est limité en surface et adapté à la petite agriculture dans les régions semi-arides du Sahel et de l'Afrique orientale où les eaux souterraines qui sont fiables et durables pourraient améliorer les moyens de subsistance des petits exploitants en augmentant la production agricole, la productivité et la sécurité alimentaire. Au cours de cette étude, plusieurs possibilités de recherches additionnelles ont émergé. Cela inclut une adaptation de la méthodologie à une échelle locale pour prendre en considération d'autres paramètres dans les calculs et une quantification de la production agricole des cultures qui pourraient être irriguées par les eaux souterraines renouvelables, si le potentiel était exploité. En complément, les futures estimations de la recharge dans le contexte du changement climatique pourraient être intégrées dans les calculs et une attention particulière pourrait être portée sur les zones frontalières ayant un potentiel de développement.

Table of content

ACRONYM

AEI	Area Equipped for Irrigation
ADB	African Development Bank
AU	African Union
BGS	British Geological Survey
CAADP	Comprehensive Africa Agriculture Development Programme
CAR	Central African Republic
DESA	Department of Economic and Social Affairs (United Nation)
DRC	Democratic Republic of the Congo
DREAM	Danish Institute for Economic Modelling and Forecasting model
FAO	Food and Agriculture Organization of the United Nations
IFPRI	International Food Policy Research Institute
IRENA	International Renewable Energy Agency
IWMI	International Water Management Institute
GAEZ	Global Agro-ecological Zones
GDP	Gross Domestic Product
GIS	Geographic Information System
GWI	Groundwater irrigation
GIDD	Groundwater Irrigation Development Driver
GIDP	Sustainable Groundwater Irrigation Development Potential
GIRP	Sustainable Groundwater Irrigation Potential (GWIP when 70% of recharge goes to the environment)
GWIP	Groundwater Irrigation Potential
GRUMP	Global Rural-Urban Mapping Project
ICRISAT	International Crops Research Institute for the Semi-Arid Tropics
HWSD	Harmonized World Soil Database
MDG	Millennium Development Goals
NASA	National Aeronautics and Space Administration
NEPAD	New Partnership for Africa’s Development
NERC	National Environment Research Council

PCR-GLOBWB	PCRaster GLOBal Water Balance model
SDG	Sustainable Development Goals
SEDAC	Socioeconomic Data and Applications Centre
SSA	Sub-Saharan Africa
SPAM	Spatial Production Allocation Model
SRTM	Shuttle Radar Topography Mission
SWAT	Soil and Water Assessment Tool
UNECA	United Nations Economic Commission for Africa
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organisation
USD	United States Dollar
WFS	World Food Summit
WWF	World Wildlife Fund

"Over the coming decades, feeding a growing global population and ensuring food and nutrition security for all will depend on increasing food production. This, in turn, means ensuring the sustainable use of our most critical finite resource – water."

UN Secretary-General Ban Ki-moon[1]

---

[1] Message delivered at the opening ceremony of World Water Day 2012 (http://www.un.org/sg/STATEMENTS/index.asp?nid=5938)

1 Introduction

In the context of climate change (i.e., temperature increase, rainfall intensity variability, droughts, and floods) (Turral et al, 2011; Taylor et al, 2013; Wheeler and Von Braun, 2013) and population increase (Godfray et al, 2010; Grafton et al, 2015), food security has been identified as a global concern, especially for poor populations in arid and semi-arid regions. The following sections review research in Africa and describe the African circumstances regarding food security, explaining the link between food security and irrigation, and detailing the current use of groundwater as a water source for irrigation.

1.1 Food insecurity in Africa

Food security is a complex development issue linked to food production and health through factors such as malnutrition, economic development, the environment, people's livelihoods, and trade.

1.1.1 Definition of food security

According to (FAO, 1996), food security is achieved "when all people, at all times, have physical and economic access to sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active and healthy life." This is the most recent definition from the World Food Summit of 1996 and is now commonly used after decades of official rethinking of the food security concept, which originated in the mid-1970s (FAO, 2003). Thus, food security is determined by four primary considerations: (i) the physical availability of food, (ii) economic and physical access to food (i.e., food trade and access to food markets), (iii) food utilisation (i.e., a sufficient and diversified diet), and (iv) the stability of the first three factors over time (FAO, 2008). Food availability refers here to the availability of food within a country; this is achieved through food production (agriculture), stock levels, and trade. Although some argue that global food production is currently adequate to feed the world[2], issues arise concerning food distribution and population growth. Food, or access to climate-adapted seeds for cultivating crops, is not affordable for the poorest populations (FAO and ICRISAT, 2015). Also, non-food crops (e.g., biofuel) are now competing with food crops (DESA, 2013). It is now acknowledged that food production needs to increase by 77% in developing countries by 2050 to achieve food security (Alexandros and Bruinsma, 2012), which intensifies the current pressure on water resources.

1.1.2 The African context

Africa is the world's second largest and second most populated continent after Asia. With an approximative area of 30 million km^2, Africa measures 8000 km from North to South, and 7400 km from East to West, covering 22% of Earth's total emerged landmass. Cultivated lands (area under temporary and permanent crop) are estimated at 2,1 million km^2 or 27% of the cultivable land (the area potentially fit for cultivation) which in turn is estimated at 7.8 million km^2 (Frenken, 2005). Figure 1 presents the topography and the sub-regions of Africa, including Sub-Saharan Africa[3] (SSA).

---

[2] http://www.wfp.org/hunger/causes

[3] Encompasses all African countries except Northern African countries (UN sub-region definition)

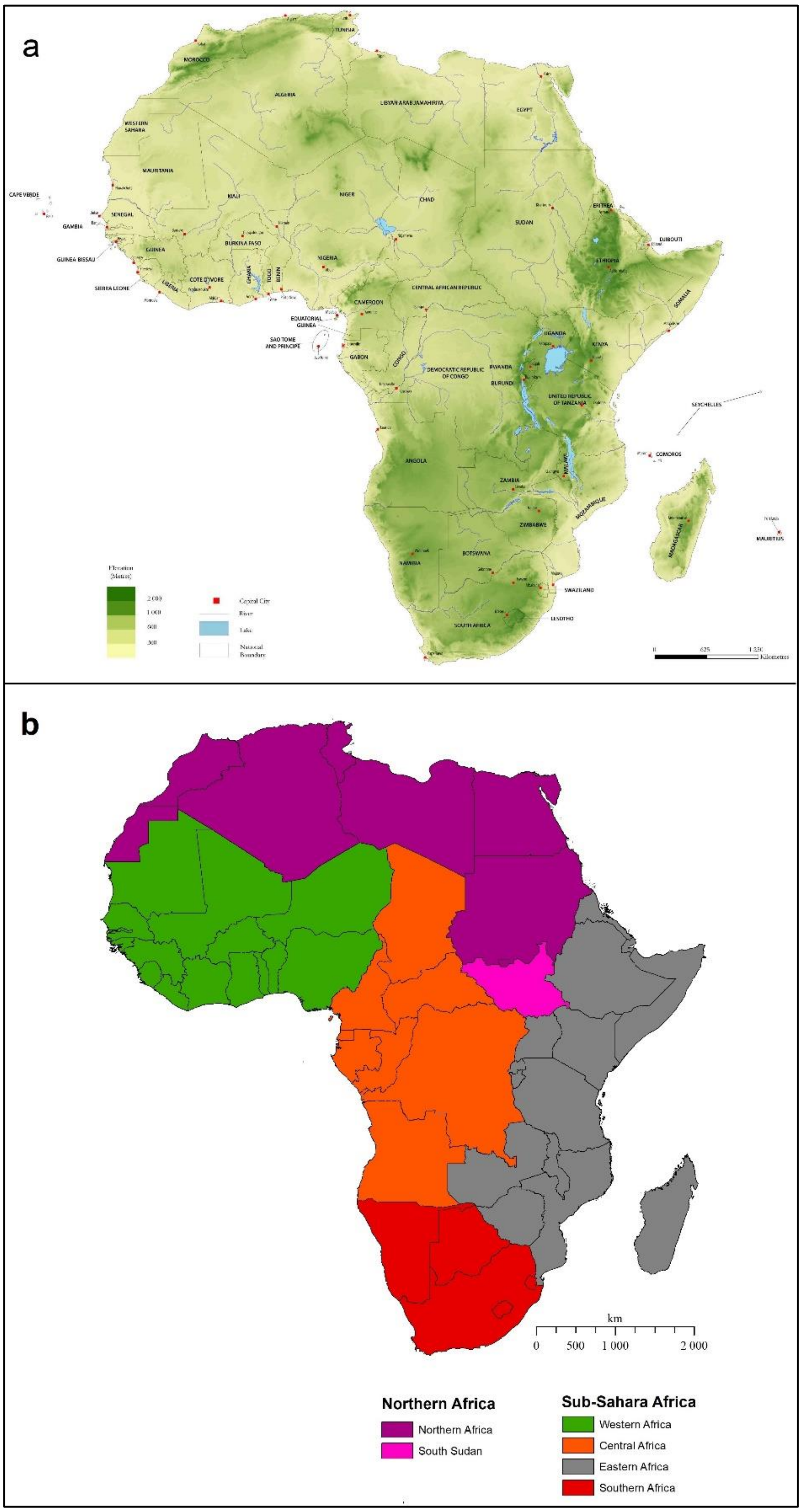


Figure 1 : (a) Topography of Africa (UNEP, 2008) and (b) Sub-regions of African according to United Nations definition of regions[4].

---

[4] https://esa.un.org/unpd/wpp/General/Files/Definition_of_Regions.pdf

1.1.2.1 Population growth and rural poverty

More than half of the global population growth between 2015 and 2050 is expected to occur in Africa representing an additional 1.3 billion African people compared to a world population increase of 2.4 billion people (DESA, 2015); this means that the African population is expected to double from 1.2 billion people in 2015 to 2.5 billion in 2050 (Figure 2a). Furthermore, Africa is the only sizable area expected to experience substantial population growth after 2050. In addition to experiencing the highest rate of population growth among major areas, growing at a rate of 2.55% annually between 2010 – 2015, Africa is a young continent. Children under age 15 comprised 41% of the African population, and people under age 24 accounted for 60% of its population in 2015 (DESA, 2015). However, there are disparities among the population growth rates of various African sub-regions: between 2015-2050, Central Africa is projected to attain the highest growth rate at 2.5%, followed by Eastern and Western Africa with a rate close to 2.2% (Figure 2b).

According to Beegle et al. (2016), there were more poor people in Africa in 2012 (330 million) than in 1990 (280 million) because of this rapid population growth while the percentage of people living in extreme poverty[5] dropped from 57% in 1990 to 43% in 2012. Africa failed to reach the Millennium Development Goals (MDG) of reducing poverty by 50% between 1990 and 2015 while all other developing regions succeeded (United Nations, 2015). However, the gap between more prosperous urban and impoverished rural areas is narrowing (Beegle et al., 2016) and boosting agricultural productivity is essential for poverty reduction (Christiaensen et al., 2011). Agriculture supports the livelihood of 90% of Africa's population, and it is one of the most important sources of income for 90% of Africa's rural population (Kanu et al., 2014) which represented 57% of the total population in 2014 (DESA, 2014).

---

[5] Revised to $1.9 a day in 2015 by World Bank (http://www.worldbank.org/en/topic/poverty/brief/global-poverty-line-faq)

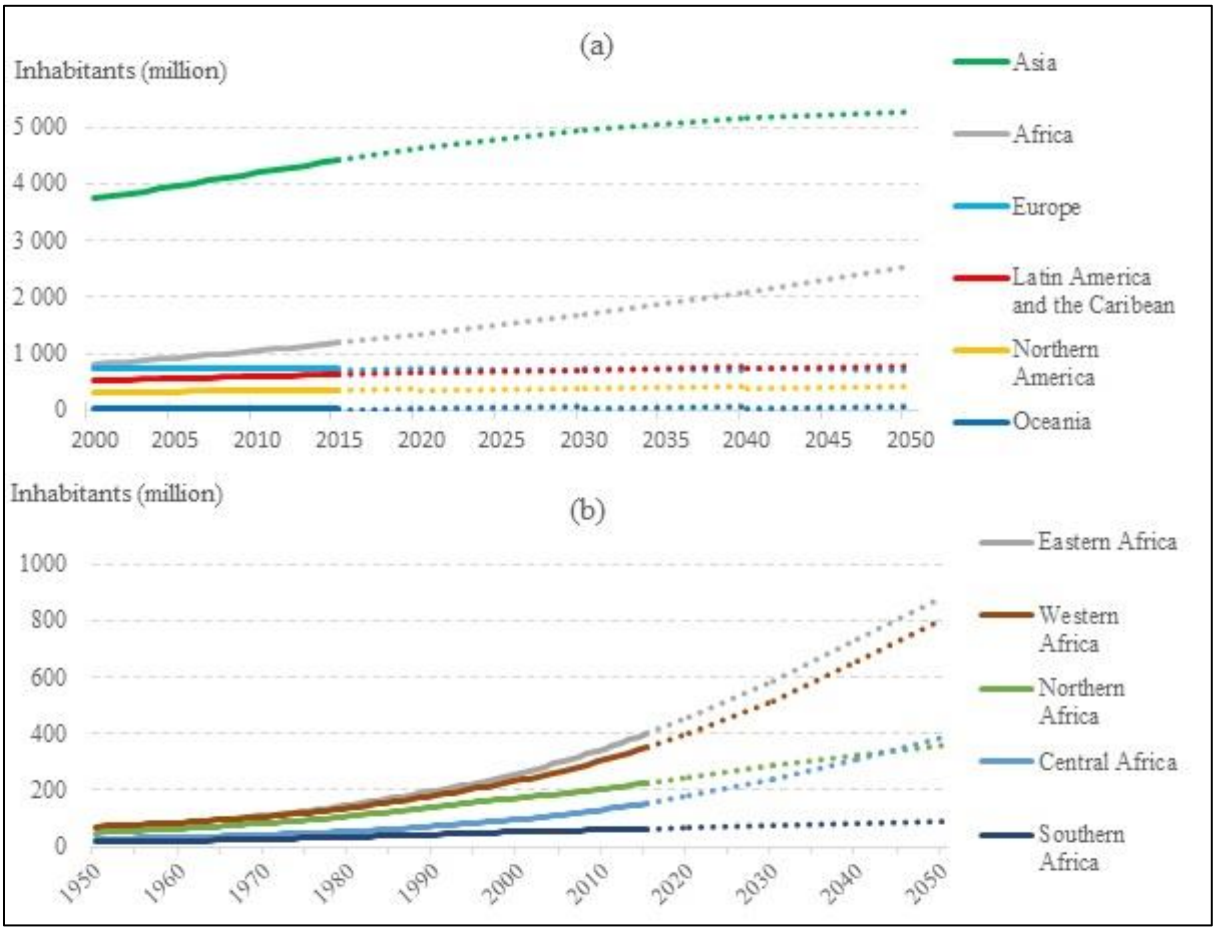


Figure 2: (a) Counted and estimates population evolution per continent over the period 2000 - 2050 and (b) per African sub-region over the period 1950 – 2050 adapted from DESA[6].

1.1.2.2 Climate

Climate greatly influences agricultural practices and productivity. While there are numerous local climate variations, the African climate is influenced by several primary factors. First, most of the continent is between the tropics. Second, there is an imperfect symmetrical arrangement of climatic zones on each side of the equator because the sea influence extends farther inland in the narrow width at the southern end of the continent. Third, cool ocean currents influence the neighbouring shore's climate (e.g., the Namib desert is due to the cold Benguela current which reduces rainfall). Fourth, the lack of high and extended mountains and the presence of large plateau surfaces explain the absence of abrupt climate changes over the continent.

---

[6] The UN DESA database is accessible at https://esa.un.org/unpd/wpp/Download/Probabilistic/Population/

Finally, mountains such as the Highlands in Ethiopia or the Kilimanjaro, the highest mountain in Africa, have unique climates based on altitude.

Figure 3 presents thirteen climate classes identified in Africa according to the Köppen-Geiger climate classification (Kottek et al., 2006; Peel et al., 2007) and the annual rainfall distribution over the continent. In Africa, rainfall is primarily seasonal and influenced by the two principal components of the African Monsoons: the West African Monsoon characterised by rainfall over West Africa from June to September (Nicholson, 2013) and the East African Monsoon characterised by extended rains from March to May and abbreviated rains from October to December (Funk et al, 2015). Africa can be broadly divided into five climatic zones based on a combination of temperature, precipitation, and evapotranspiration (Ngaira, 2007; UNEP, 2008).

The arid and semi-arid areas cover more than 30% of the continent and include, from north to south, the Sahara Desert, the Sahel region, the Eastern part of the Horn of Africa, the Kalahari and the Namib desert. Annual rainfall ranges from less than 50 mm per annum in the Sahara Desert and the Namibian coast to 500 mm per annum in some parts of the Kalahari and Sahel. These areas correspond to the less favourable regions for rainfed agriculture (Droogers et al., 2001).

The equatorial area is characterised by a hot, humid climate with two rainier seasons (March to May and September to November) and two drier seasons (June to August, and December to February). The region is located from the southern part of the West Africa coast to the north of the Democratic Republic of Congo where rainfall can be as high as 2500 mm per year. Rainforest is found in most of the Congo Basin. Rainfed agriculture has the highest potential in these areas (Droogers et al., 2001).

The tropical area extends from the South of the Sahel to the north of the continent's southern tip. The area covers about 50% of the continent and rainfall depends on the monsoons (generally rainy summer and drier winter seasons). It can be divided into humid tropical areas which are found at the proximity of the equator (i.e., south of the Western Africa coast and Central Africa) and drier tropical areas which are characterised by long dry seasons and correspond to the savanna grassland located to the north and south of the humid tropical zones. The monsoon drives the seasonal rainfall which ranges from 600 to 1200 mm per year in the dry tropical zone to 1100 to 1800 mm in the humid tropical zones. The potential for rainfed agriculture is generally intermediate compared to the two previous climatic zones with humid tropical areas having higher potential than the dry tropical zones (Droogers et al., 2001).

The Mediterranean climate areas dominate the northern and southern continental extremes (i.e., North Africa Coast and Cape region in South Africa) and are characterised by hot, dry summers and mild, rainy winters. Rainfall can be as high as 800 mm per year. Rainfed agriculture potential is equivalent to the dry tropical zone.

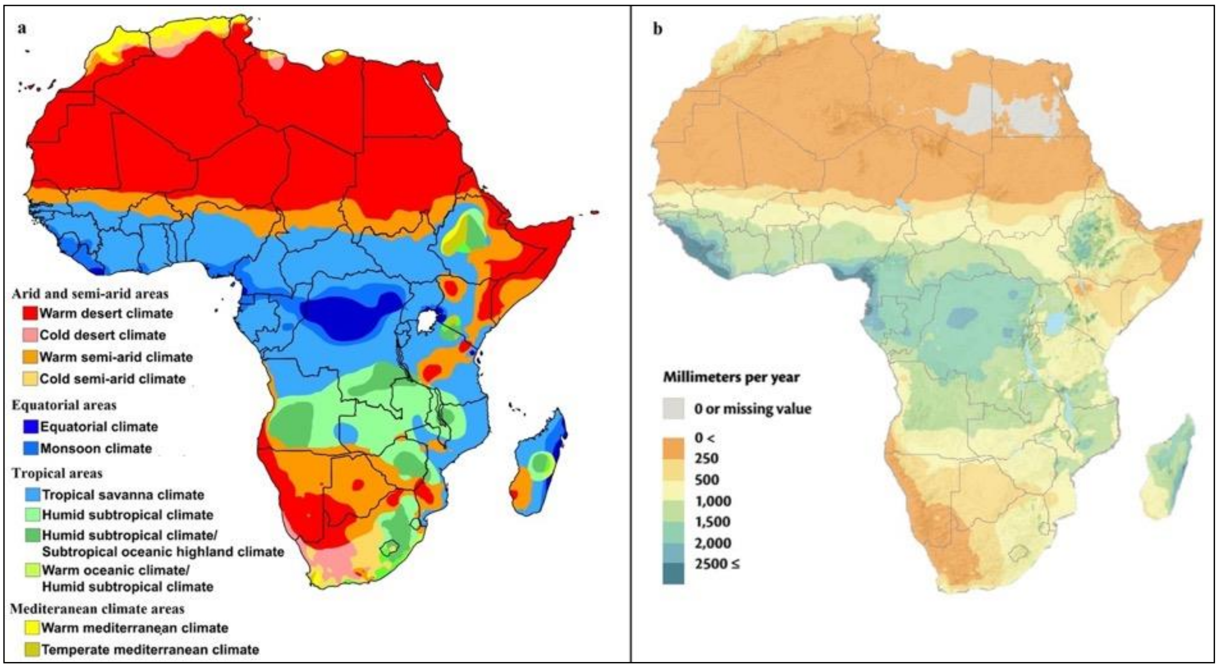


Figure 3: (a) Köppen-Geiger climate classification adapted from Peel et al (2007) and (b) average annual rainfall distribution in Africa over 1970-2000 expressed in mm/year adapted from IFPRI (2014).

Concerning climate change, there is a high level of confidence that climate change will compound the existing stress on water availability in Africa (Niang et al., 2014). While mean annual temperatures will likely rise by more than 3°C by the end of the 21st century, precipitation is projected to decrease over North Africa and Southwestern parts of South Africa, but there is a very high level of uncertainty concerning precipitation trends over most of the continent (Ongoma et al., 2017; Osima et al., 2018; Roudier et al., 2014). Some areas might experience increases in rainfall and extreme rainfall. As a consequence of temperature increases and precipitation changes, there is a likely risk of crop productivity reduction which could significantly impact food security in Africa (Adhikari et al., 2015; Niang et al., 2014; Parkes et al., 2018; Zinyengere and Crespo, 2017).

1.1.2.3 Geology and groundwater

Groundwater occurrence depends primarily on geology, geomorphology/weathering and both current and historic rainfall (MacDonald and Calow, 2009). These factors interplays to create complex and countless hydrogeological conditions which affect quantity, quality, access and renewability of the groundwater resource. This section describes, in link with the geology, the main aquifer types that can be found in Africa and it is based on MacDonald and Davies (2000), Seguin and Gutierrez (2016) and the Earthwise website[7]. There are four simplified typology of aquifer in Africa as shown in Figure 4: the recent sedimentary rocks, the ancient sedimentary rocks, the crystalline basement rocks and the volcanic rocks.

The recent sedimentary rocks cover more than 50% of the African area. These formations can be divided into five main type of aquifers:

- Deep aquifers are located mainly in Northern and Western Africa. These deep aquifers have generally non-renewable groundwater and includes large aquifers such as the Nubian Sandstone Aquifer System and the North Western Sahara Aquifer System.
- Unconfined aquifers can be found in the Congo Basin, the Kalahari.
- Alluvial aquifers are found along the rivers in semi-arid and arid areas. These aquifers exist also along intermittent rivers and represent an important water source for rural population.

---

[7] http://earthwise.bgs.ac.uk

- The Karoo (or Karoo Supergroup) is a complex geological structure which consists of a sequence of sedimentary rocks, mostly of nonmarine origin, intercalated with volcanic rocks. It covers two thirds of Southern Africa corresponding to 3.5% of the total African area. Storage and permeability is limited but sandstone layers have better groundwater potential. Groundwater flow is largely via fractures and other discontinuities.
- The carbonate rocks covers important areas in DRC and Ethiopia but also in Nigeria and Gabon. They covers about 9% of the total African area. Aquifers in carbonate rocks are particularly interesting when karstification occurs (dissolution of the rock by rainfall) increasing borehole yield and aquifer storage. Karst is mainly present in North Africa, Madagascar and Southern Africa.

The ancient sedimentary rocks correspond to fractures and very consolidated rocks. From an hydrogeological view, they can be assimilate to crystalline basement rocks. They cover 21% of Africa and are located at the edge of the large sedimentary basin (e.g. Congo Basin, Kalahari Basin or North Western Sahara)

The crystalline basement rocks occupy about 21% of the land area of Africa. Groundwater is found where the rocks have been significantly weathered or in underlying fracture zones. Borehole and well yields are generally low, but can be sufficient for rural demand.

The volcanic and plutonic rocks cover 4% of the land area of Africa and are located mainly in Eastern Africa. Groundwater is found within palaeosoils and fractures between lava flows. Groundwater potential of these formations varies considerably depending on the geology complexity. Despite their small extent, they are highly significant aquifers since they underlie much of the poorest and drought stricken areas of Africa. Yields can be high, and springs are important in highland areas.

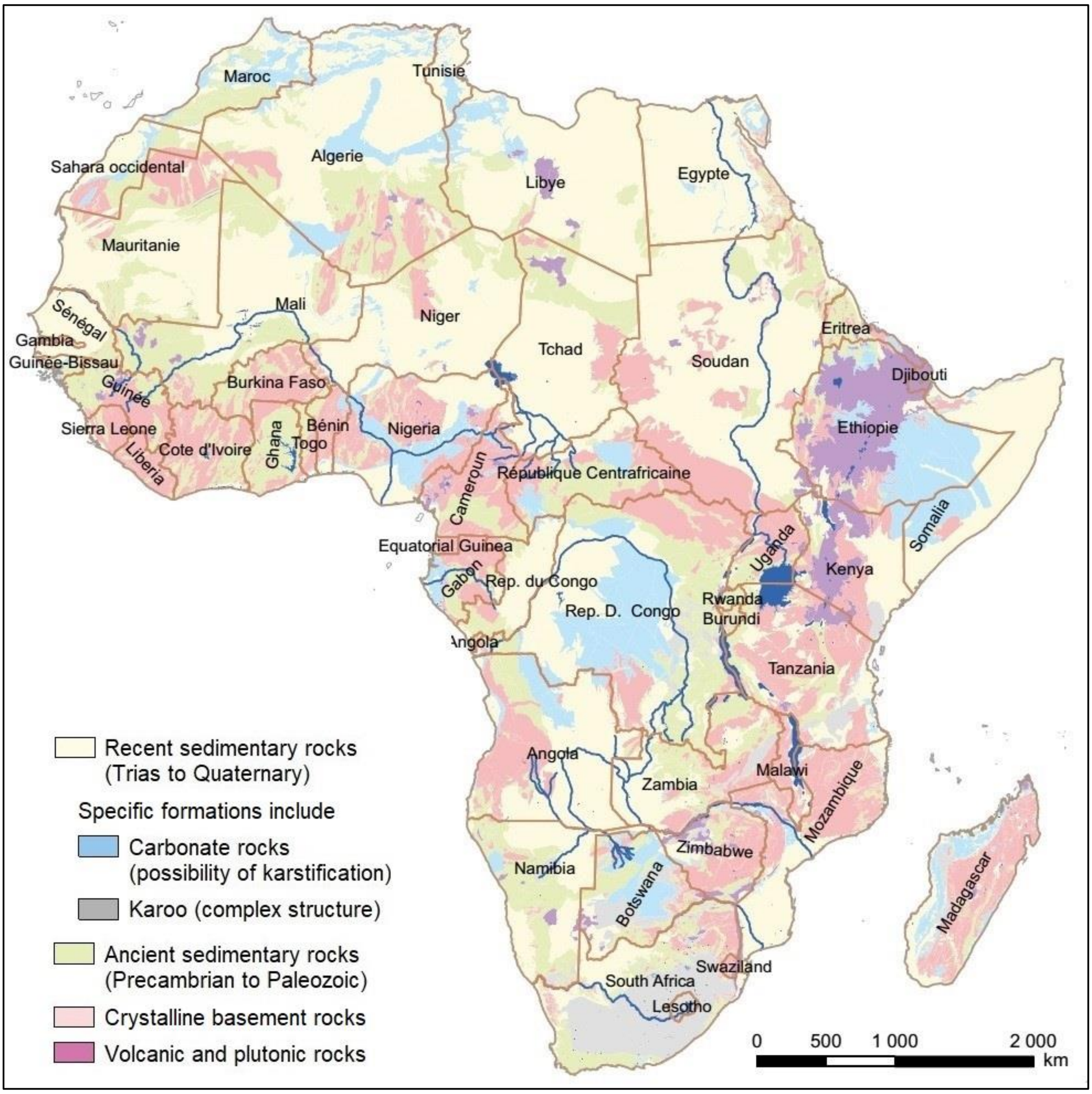


Figure 4: Main aquifer typology in Africa, adapted from Seguin and Gutierrez (2016)

1.1.3 The level of food insecurity in Africa

One method to approach global food insecurity is to examine hunger since all hungry people contend with food insecurity. Figure 5 presents recent data from the FAO et al. (2015) and DESA (2015) regarding past and projected total population, undernourished people, and the prevalence of undernourishment in those regions of the world affected by hunger. The number of undernourished people in Africa grew by 51 million, rising from 182 million in 1990 to 233 million in 2015, whereas the percentage of undernourishment prevalence in Africa decreased from 27.6% to 20.0% for the same period. Results indicate that there is an effort to reduce hunger in Africa, but it is insufficient to catch up with the population growth. Asia presents a more encouraging situation, since the percentage of undernourished individuals has halved and, more importantly, has been accompanied by a reduction of approximately 230 million hungry people over the same 25-year period, while Latin America and the Caribbean region have reduced prevalence to about 5%.

By comparing it with the other regions, it is apparent that Africa still has a critical food insecurity problem. DESA (2015) provides past and future population data, the latest being estimated by using projections based on medium fertility. Africa’s population increased by 573 million in the period 1990–2015, whereas Asia added 1,184 million to its population. Figure 5 shows that Asia sufficiently fed 1,414 million additional people, while Africa fed an additional population of 522 million over the 25-year period, corresponding to 31.7% and 35.5% of the 2015 population, respectively.

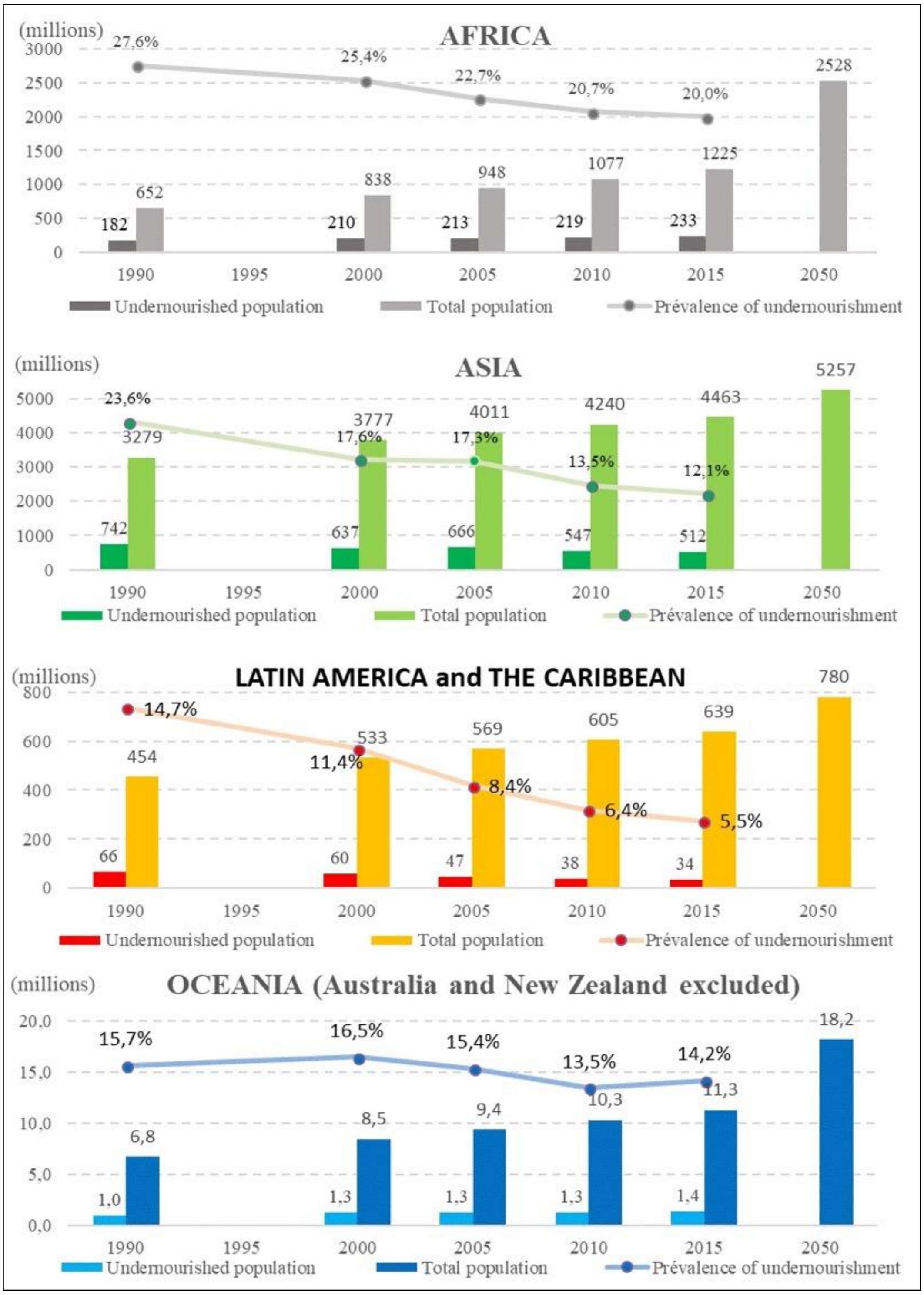


Figure 5: Counted and evaluated undernourished population during the period 1990–2050 in the world, adapted from FAO et al. (2015) and DESA[8].

---

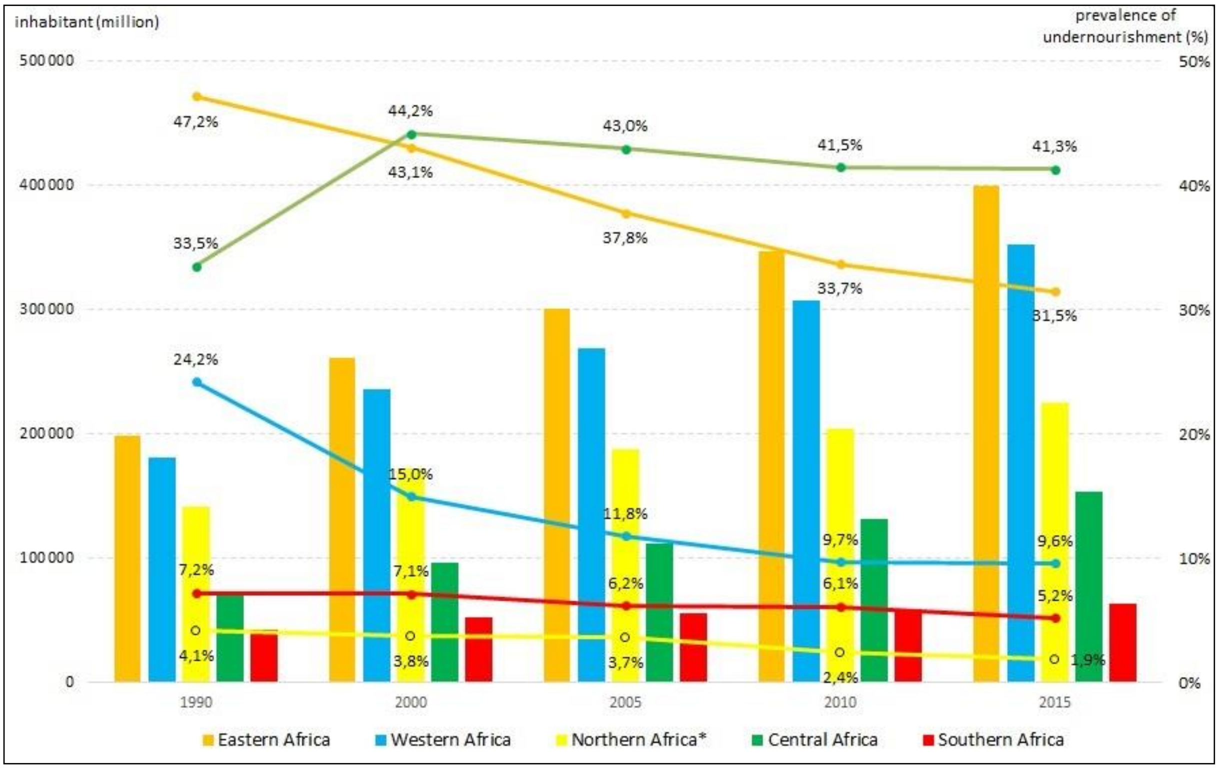
[8] The UN DESA database is accessible at https://esa.un.org/unpd/wpp/Download/Probabilistic/Population/

However, the projected data indicates that the populations will grow to 2,528 million in Africa and 5,257 million in Asia by 2050[9]. Compared to the 2015 population, this means that the African population will double while the Asian population will increase by only 17.1%. Consequently, the African demand for food will increase substantially. According to Alexandros and Bruinsma (2012), food production in developing countries must increase by 77% from 2007 to 2050. Crop production increases over the same period need to be approximately 151% and 68% in SSA and East Asia, respectively. Also, Africa is particularly dependent on imported food, and food production in the region continues to lag due to limited research investments and the inefficient use of appropriate inputs by farmers during the production process (Nellemann et al., 2009). Thus, Africa must face the reality of significantly increasing food production to guarantee the availability of food and the future demand. It is important to note that the African sub-regions face different situations concerning food security as shown in Figure 6.

Northern Africa has a low prevalence of undernourishment—under 5%—which is close to that of Western countries because of subsidized access to food, irrigation development (mainly with non-renewable water resources) and food imports (FAO et al, 2015), while Central and Eastern Africa face a very high prevalence of undernourishment—over 30%. This statistic indicates that efforts for increasing both food access and food production in Africa should focus primarily on SSA where a quarter of its population is suffering from chronic hunger.

---

[9] The UN DESA database is accessible at http://esa.un.org/unpd/wpp/unpp/panel_population.htm.



*calculated from DESA database

Figure 6: Total population and prevalence of undernourishment in African sub-regions, adapted from FAO et al. (2015) and DESA[10]

1.1.4 Toward the Sustainable Development Goals

Concerning the Millennium Development Goals (MDG), Africa made progress toward achieving the MDG 1.C target, which was halving the proportion of its population suffering from hunger between 1990 and 2015. Overall, Africa reduced the prevalence of undernourishment from 27.6% in 1990 to 20.0% over the 25-year period (FAO et al., 2015). However, there are essential differences between the sub-regions (Figure 6). Northern Africa and Western Africa achieved the MDG 1.C target, but the number of undernourished people in Western Africa is still over 30 million. Southern Africa was close to attaining the target and is likely to reach it by 2020

---

[10] The UN DESA database is accessible at https://esa.un.org/unpd/wpp/Download/Probabilistic/Population/

(FAO, 2015). Unfortunately, Eastern and Central Africa failed to achieve the target, particularly Central Africa where the prevalence of undernourishment increased over the period.

The situation is worse when it is compared to the World Food Summit (WFS) target of reducing by 50% the number of undernourished people by 2015. Africa increased the number of undernourished people from 182 million to 233 million between 1990 and 2015. None of the sub-regions succeeded in achieving the target and only Northern and Western Africa reduced the number of undernourished people over the 25-year period. Thus, it is necessary to improve food access and food production in the region.

The United Nations adopted the 17 Sustainable Development Goals (SDGs) of the 2030 Agenda for Sustainable Development on the 25th of September 2015[11]. The SDG 2 is focused on ending hunger, achieving food security and improving nutrition, and promoting sustainable agriculture. It is divided into eight targets and fourteen indicators[12]. While the linkages between the goals and the targets are complex as actions taken to achieve one goal might be mutually reinforcing or contradictory to achieving another goal (Zhou and Moinuddin, 2017), this thesis focuses primarily on SDG 2.1 and 2.4 targets. The SDG 2.1 target is ending hunger by 2030 and ensuring access by all people, particularly the poor and those in vulnerable situations, including infants, to safe, nutritious and adequate food year-round. SGD 2.4 pertains to ensuring sustainable food production systems by 2030 and implementing resilient agricultural practices that increase productivity and production, help maintain ecosystems, strengthen capacity for adaptation to climate change, extreme weather, drought, flooding, and other disasters while progressively improving land and soil quality.

---

[11] http://www.un.org/sustainabledevelopment/blog/2015/09/historic-new-sustainable-development-agenda-unanimously-adopted-by-193-un-members/

[12] https://sustainabledevelopment.un.org/sdg2

1.2 Groundwater irrigation as a tool for increasing food security in Africa

While there are several methods to reduce hunger and food insecurity (i.e., food import or subsidizing access to food), irrigation was recognized as part of the foundation to achieve the MDG for hunger and poverty (Polack, 2004) and it is still recognised as a critical element for achieving the SDG and increasing food security in Africa (AU et al., 2017). This thesis focuses on sustainable groundwater irrigation to increase crop production and food security in Africa. This section presents how groundwater irrigation can mitigate food insecurity.

1.2.1 Increasing crop production for improving food security in Africa

In Africa, an important tool to boost food security is to improve access to food by increasing food production, particularly crop production. During the 2005–2007 period, the composition of food in SSA was 340 kg of crop totaling 381 kg of food per person per year. Crops contributed to 89% of the diet in SSA, and the ratio is similar for the projected total commodity of food, which should increase from 381 kg to 414 kg by 2030 and then to 435 kg by 2050 (Alexandros and Bruinsma, 2012). In addition to the necessary increase in food production for direct human consumption, food production for animal-feed and non-food (i.e., biofuel) must be considered. The total crop production in 2050 should be 1.5 times higher than in 2007. Thus, the development of crop production is a major factor regarding increasing food production (including livestock and fisheries) and thereby food security.

Growth in crop production results from an expansion of the physical area allocated to crops, as well as crop yield improvement and increases in cropping intensities (i.e., by increasing multiple cropping and shortening fallow periods each year). These circumstances contribute to expanding the quantity of the harvested crop (Alexandros and Bruinsma, 2012). SSA food production growth between 1960 and 2000 was mainly due to extending the area being cultivated and better cropping intensities rather than yield improvement (Evenson and Gollin, 2003). The rate of variation for the cultivated land (food crop and non-food crop areas) has increased by 33% in SSA from 1960 to 2000 and is projected to increase three times more in SSA than in Asia from 2000 to 2050 (Paillard et al., 2011). A closer examination of the possible cultivation expansion areas shows that six African countries[13] cumulatively possess more than 80% of the non-forested underutilised land areas; the Democratic Republic of Congo represents slightly less 50% alone (Fisher and Shah, 2010; Jayne et al., 2014). Chamberlin et al. (2014) indicate that many studies based on land and climate characteristics in association with biophysical production characteristics agree on arable land being abundant as a whole in Africa, but they emphasise that potential extents have limited economic attractiveness (e.g., land can be isolated from market or public services and under social conflicts). Given this fact, improving crop yield seems to represent a vital consideration in increasing food production in Africa.

1.2.2 Irrigation as tool for increasing crop production in the African context

Crop growth and development are subject to abiotic and biotic factors that restrict yield (e.g., lack of water and nutriments) and reduce yield (e.g., pests and diseases) (Haverkort and Schapendonk, 1994). Because of these environmental stress factors, there is a limitation on the full attainment of the potential crop yield (Fageria et al., 2010). However, farmers can control some factors through appropriate crop management practices (i.e., water, cultivar characteristics, nutriments, insect and diseases) to increase the crop yield. Crop yield growth can be broken down into the contributions of high-yield crop varieties and the contributions of all other inputs (e.g., fertiliser, irrigation, mechanisation, and labour). In fact, irrigation has proved to boost food productivity directly. Irrigation investments in Asia from the 1960s to the 1980s played a vital role in facilitating the adoption of productivity-enhancing technologies of the Green Revolution[14] (Pingali et al., 2016). Unfortunately, SSA experienced an incomplete Green Revolution from 1961–2000 due to the region’s difficulties with producing high-yield crop varieties adapted to its specific agro-ecological complexities (Evenson and Gollin, 2003). This situation translated into a relatively low crop yield increase of 38% in SSA, as compared to a greater than 75% increase in Asia during the same 1961–2007 period (Alexandros and Bruinsma, 2012). Asian and Latin American countries experienced yield increase and accelerated agricultural output during the

---

[13] The Democratic Republic of Congo, Angola, Congo, Zambia, Cameroon, and Mozambique

[14] The term “Green Revolution” was first used by William Gaud in 1968 and now refers to dramatic yield improvement due to the development of high-yield crop varieties, the expansion of irrigation infrastructure, the modernisation of management techniques, and better use of fertilisers and pesticides

1960s and 1970s due to the adoption of high-yielding varieties of wheat, rice, and maize, combined with the intensive use of inputs such as fertiliser and irrigation (Nin-Pratt and McBride, 2014). Consequently, the current situation in Africa indicates that crop yield increases can be accomplished primarily through crop inputs though there is still potential for developing high-yield crop varieties.

Mueller et al. (2012) demonstrate that global yield variability is mainly dictated by fertiliser use, irrigation, and climate. While some crops (e.g., sorghum) are more sensitive to climate, others (e.g., barley) are very responsive to better nutrient and water management. Yield increases of 45%–70% are possible for most crops through improved nutrient management and the increased use of irrigation. For example, SSA shows considerable short-term intensification opportunities for major crops: maize yield can be increased to 50% of its attainable yield primarily by addressing nutrient deficiencies and can be increased by up to 75% of its attainable yield by increasing irrigated areas and nutrient application (Muller et al., 2012). There are several examples from around the world which indicate that irrigation was the primary driver for increasing crop yield and productivity. Fischer et al. (2014) demonstrate that wheat yield in New Zealand doubled since the 1900s because there was a transition from zero to 80% irrigated area over the period. Without irrigation, rice yield in Southeast Asia is only 60% of the yield obtained in irrigated areas, and similar yield differences are found for wheat in Central Asia and cereals in Argentina and Brazil (Godfray and al, 2010). Also, Siebert and Döll (2010) calculated the potential production losses without irrigation during the period 1998-2002. They show that production loss for cereals in Africa is close to 80% when not using irrigation (compared to production in irrigated areas), corresponding to a drop of cereal crop yield from 428 Mg/km^2 in the irrigated land to 102 Mg/km^2 in rainfed areas. This finding represents the world's largest production loss. Thus, irrigation can play a significant role in increasing crop yield, food production and food security in Africa, especially when complemented with inputs (i.e., fertilisers and pesticides).

1.2.3 The slow development of irrigation in Africa

While there is definite interest to irrigate for increasing crop production, irrigation development in Africa has been very slow compared to other continents. The evolution of worldwide irrigated areas for the period 1970–2015 is shown in Figure 7 and Table 1. For display clarity, Asia has been split into Southern, Central and Western Eastern; and Eastern and South-Eastern Asia on Figure 7. The irrigated areas are compared to the cropland[15] areas which correspond to the arable land[16] and the permanent crops[17]. The development of the area equipped for irrigation has been very significant in Asia as compared to Africa, which increased its area equipped for irrigation by only 7.4 million hectares over the 45-year period, while Asia saw an increase of 116.9 million hectares, corresponding to a similar multiplication of the irrigated area by 2.0 for both continents. However, the increase in the percentage of cropland over the 45-year period is very significant in Asia (25.8% to 40.4%) compared to Africa (from 4.5% to 5.8%). In fact, Africa exhibits the world's lowest percentage increase.

---

[15] Cropland land or cultivated land is used here interchangeably to mean the combined arable land area and the area with permanent crops (http://www.fao.org/nr/water/aquastat/data/glossary/search.html?lang=en).

[16] Arable land is the land under temporary crops, temporary meadows for mowing or pasture land under market and kitchen gardens and land temporarily fallow (for less than five years)

[17] Land under permanent crops is the land cultivated with crops that occupy the land for long periods and need not be replanted after each harvest.

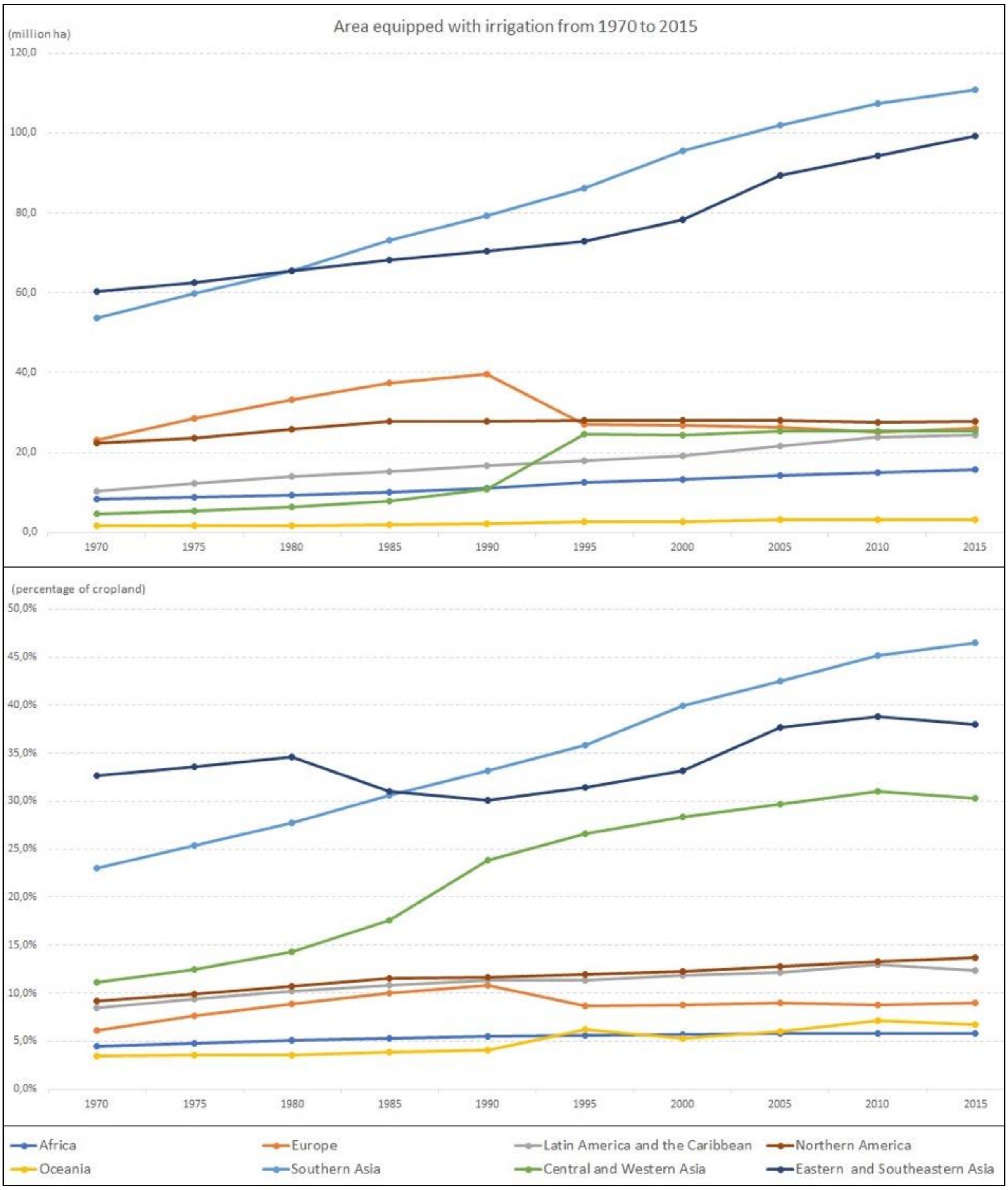


Figure 7: Evolution of the area equipped with irrigation for the 1970–2015 period expressed in millions of hectares and percentage of cropland, adapted from FAO statistics database.

Table 1: Area equipped for irrigation (AEI) per continent for the year 1970 and 2015 expressed in million hectares and compared to the cropland, adapted from FAO statistics database.

	1970		2015		over the period 1970 -2015	
	AEI (10^6 ha)	AEI as percentage of cropland (%)	AEI (10^6 ha)	AEI as percentage of cropland (%)	total increase in AEI (10^6 ha)	multiplication factor of AEI
Africa	8.4	4.5%	15.8	5.8%	7.4	1.9
Europe	13.0	6.1%	26.0	9.0%	13.0	2.0
Asia	118.7	25.8%	235.6	40.4%	116.9	2.0
North America	22.3	9.2%	27.9	13.7%	5.6	1.3
Latin America and the Caribbean	10.3	8.4%	24.4	12.4%	14.1	2.4
Oceania	1.6	3.5%	3.3	6.7%	1.7	2.1

Figure 8 shows the evolution of the cropland and the area equipped for irrigation of the African sub-regions over the period 1975-2015. The areas equipped for irrigation in Africa increased by 44% during this period, but this still represents less than 6% of the total cropland. There are substantial variations in irrigation development throughout Africa. Over these four decades, the higher growth rates of areas equipped for irrigation are in Western and Eastern Africa with more than a 60% increase, but the area equipped for irrigation is still minimal, corresponding to a bit more than 4% and 1% of the cropland in Eastern Africa and Western Africa, respectively. By comparison, Northern Africa has the lowest growth rate (33%) over the four decades, but the area equipped for irrigation reached 19% of the total cropland in 2015.

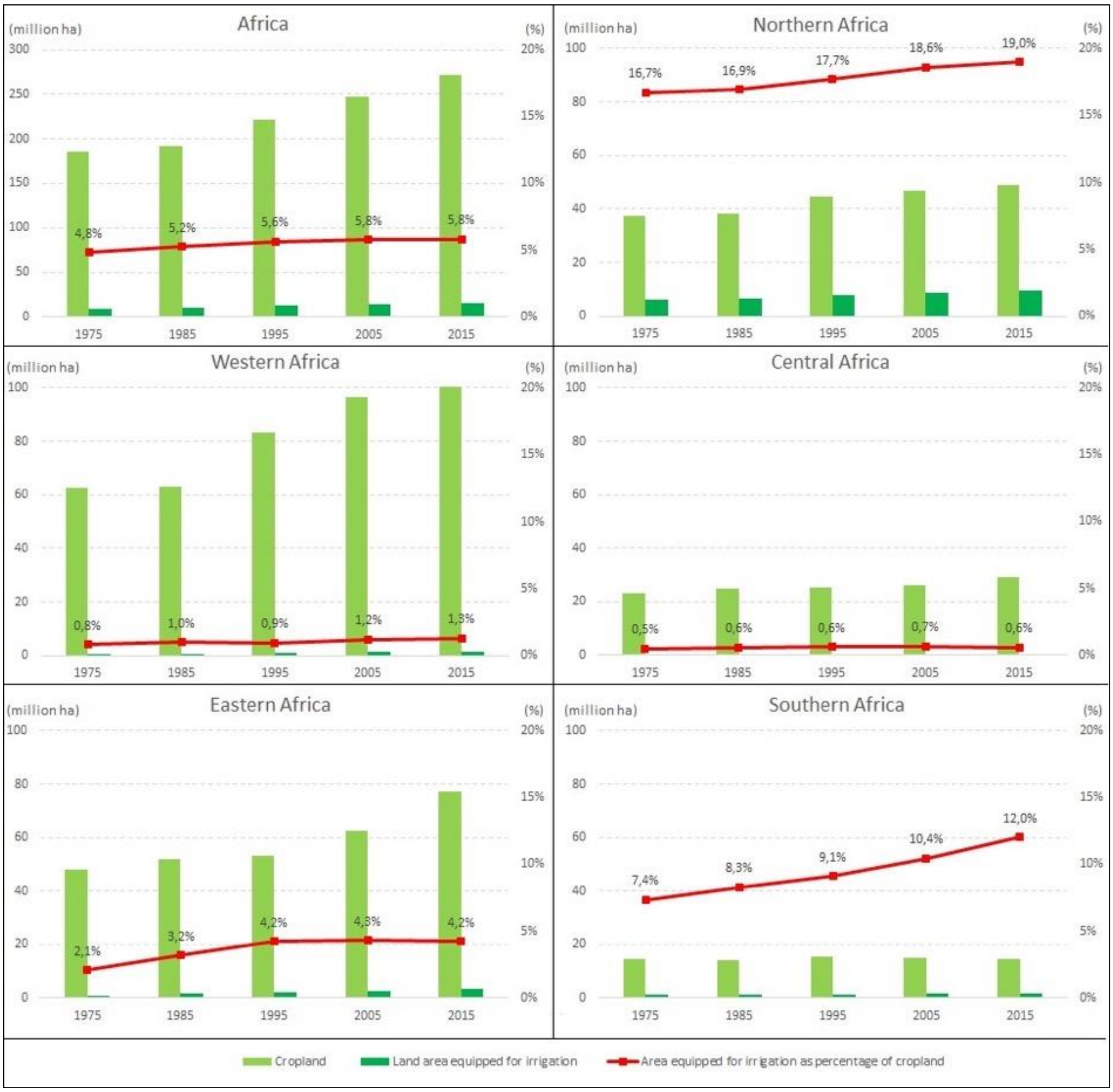


Figure 8: Evolution of cropland land expressed in million hectares, and total area equipped for irrigation expressed in millions hectares and in percentage of cropland for the African sub-regions over the 1975-2015 period, adapted from FAO statistics database.

There are several reasons for slow irrigation development in Africa. After the initial government-driven development of irrigation schemes near large perennial rivers (e.g., Niger, Senegal, Nile, Volta, Zambesi), at the end of the 1980s irrigation in Africa underwent fundamental changes including the liberalisation of the production chain, the transfer of scheme management to users, and the emergence of environmental concerns (Frenken, 2005). Also, project costs were found to be excessive in Africa compared to the rest of the world (ADB et al., 2007). Donor interest for developing irrigation in Africa declined because of the lack of successful performance of the public irrigation schemes, the decline of cereal prices in the 1980s which made African irrigated crops uncompetitive compared to subsidised foreign exports, and the social and environmental concerns of poorly planned projects (Oates et al., 2015). Moreover, the policies of international institutions (i.e., market liberalisation) caused a fall in agricultural investment in the context of transitional national policies (Bryceson et al., 2010). However, the decline of public investment in large-scale irrigation after 1980 spawned the development of small private irrigation, generally unregulated and “under the radar” (Jamin et al., 2011). This type of irrigation development has been rapid in South Asia and the Maghreb, and it is now emerging in SSA (De Fraiture and Giordano, 2014).

Despite past difficulties, there is currently increasing interest for irrigation development in Africa supported by the facts that, after their failure in the 1970s and 1980s, recent irrigation projects are more cost-competitive compared to Asia, offering acceptable rates of return and poverty is limited in farming systems that are predominantly irrigated (ADB et al., 2007). African national and regional policies and plans (CAADP, 2009; NEPAD, 2003) have stressed irrigation development and more broadly sustainable land and water management as key components to poverty alleviation and gains in food productivity. Domènech (2015) described some of the advantages of irrigation: it reduces vulnerability to drought and climate change, provides greater availability and stability of food supplies during the dry season and can enable diet diversification through crop diversification (i.e., fruits and vegetables). Thus, in the context of population growth, climate change, and renewed interest, irrigation can play a crucial role in African food security if it is sustainably developed.

1.2.4 Groundwater: the underutilised water resource in Africa

There are two primary water resources for irrigation: surface water and groundwater. Other water resources for irrigation, usually called unconventional water (i.e., wastewater, desalinisation), have minimal use in Africa because of the lack of investment in infrastructures (i.e., sanitation systems). Figure 9 presents the world’s continental comparison of areas equipped with irrigation in 2005. Groundwater contributes to 18.5% of the total area equipped for irrigation in Africa, whereas that number is 38% in Asia. GWI covers around 2×10^6 ha in Africa, which is equivalent to 1% of the cultivated land; similar measurements in Asia amount to 38×10^6 ha or 14% of the cultivated land (Siebert et al., 2010).

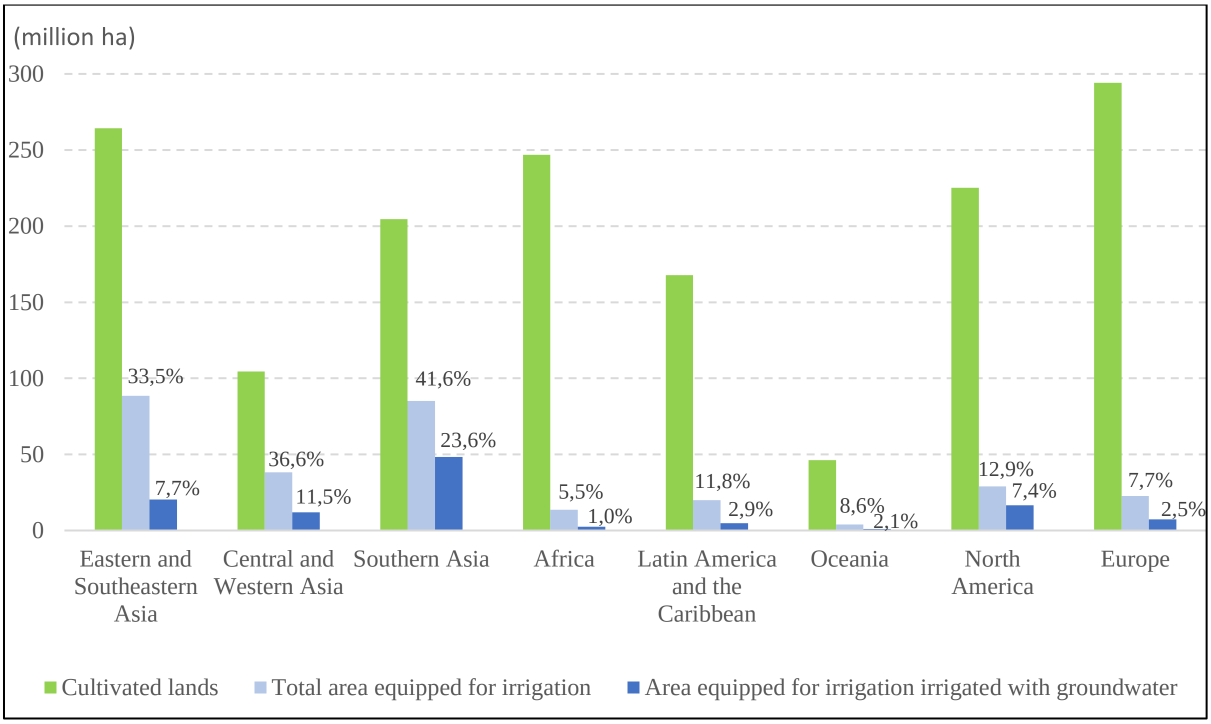


Figure 9:Area equipped for irrigation in the world for the year 2005, expressed in millions of hectares and in percentage as a fraction of the cultivated land, adapted from Siebert et al. (2010).

Since groundwater plays a critical role in Africa, as 75% of the population rely on it for domestic water supply and livestock watering (UNECA and AfDB., 2010), the limited use of groundwater for irrigation in Africa raises a question concerning the amount of current interest in this water resource for agricultural purposes. 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 irrigation, along with traditional surface water resources, particularly in Ethiopia (Ministry of Finance and Economic Development, 2010), Ghana (Ministry of Food and Agriculture, 2011), Malawi (Ministry of Irrigation and Water Development, 2005), South Africa (Department of Water Affairs, 2013) and Zambia (Ministry of Agriculture, 2004). This interest is evidenced by the fact that farmers have increasingly embraced GWI spontaneously with their own investments where conditions permit (Villholth, 2013). Calow et al. (2010) describe how groundwater is a reliable water source, especially during droughts. In fact, groundwater is affordable (particularly shallow aquifers), safe, and reliable, especially in rural Africa. It is generally less expensive to develop compared to other water resources; aquifers offer natural protection against contamination and groundwater offers a reliable supply and a buffer against drought due to its storage capacity, and it is less affected by evaporation than surface water bodies (Calow et al., 1997). Also, crop yields of groundwater-irrigated areas are typically much higher than those in surface water schemes because of its controllability, which allows for efficient and flexible use (Burke et al., 1999). Shallow groundwater is already recognised as one of the options for water sources in food production in SSA due to the growing scarcity and competition for water resources (Inocencio et al., 2003). Regardless of the negative impact of groundwater irrigation developed in Chapter 1.2.5 and to highlight the significance of utilizing groundwater for irrigation, a few success stories of its use, mainly in Asia, can be referenced. Bangladesh became almost self-sufficient regarding food grain production using irrigation over the last 30 years, as irrigation areas increased by about three times; GWI comprised 77% of all irrigation (Rahman and Parvin, 2009). In India, more than 50% of irrigated agriculture depends on groundwater, and crop yields are generally 30% to 50% higher in groundwater-irrigated areas (Foster et al., 2008). Finally, GWI in Spain consumes 20% of the total water volume of the irrigated agricultural production, but its economic value is 50% of the total economic value of irrigated agricultural production (Fornes et al., 2005).

In fact, since the 1970s groundwater has already assisted millions of farmers in Africa (and in Asia) in overcoming food poverty because small-scale GWI has promoted greater equity between groups of populations, as opposed to large-scale surface water irrigation (ADB, 2013). As previously stated, groundwater is a resource that is often easily accessible, and it is usually good-quality water if it is abstracted in a sustainable manner, rather than being mined or used for low-value purposes (ADB, 2013). Water availability is a significant concern for the African population given that SSA has the most water-stressed countries in any region. Water stress[18]

---

[18] http://epaedia.eea.europa.eu/alphabetical.php?letter=W&gid=108#viewterm

occurs when the demand for water exceeds the available amount during a specified period or when poor quality restricts its use. Some African countries, such as Kenya or Burkina-Faso, are already experiencing a water scarcity situation[19], which indicates that the amount of water withdrawn from lakes, rivers, or groundwater is so great that water supplies are no longer adequate to satisfy all human or ecosystem requirements. In this context, additional groundwater abstraction requires attention and regulation as many rivers and ecosystems are groundwater-dependent. A recent study by MacDonald et al. (2012) pointed out that Africa has vast groundwater volume but not all of it is available for extraction, and it is unevenly distributed. However, the current volume of extracted groundwater does not necessarily reflect these findings. Groundwater represents 14% of the total extracted water in Africa (mainly in North Africa, South Africa, and Nigeria), part of it being non-renewable, and only 4% of the total groundwater extracted in the world (Margat, 2010). This statistic needs to be compared to the renewable freshwater figures. According to the AQUASTAT database[20], groundwater accounts for 37% of renewable fresh water and 35% of the surface water is supported by groundwater discharge in Africa (Margat, 2010). Hence, it seems that the extraction of renewable groundwater can be developed on the continent, but there is not a precise and spatially distributed estimate of groundwater availability in Africa.

The expansion of groundwater-based irrigation in Africa faces barriers, particularly in SSA. The main obstacles are a lack of knowledge of the resource and the best options for its sustainable development. As presented previously, current levels of development are low, and most of it occurs in the informal sector. Villholth (2013) described the different constraints to further GWI development in SSA. The direct constraints are linked to physical groundwater access, including well construction and lifting devices. Labour is the primary constraint for shallow, high-yield groundwater, which can be easily accessed with manual drilling and human lifting. Deeper aquifers require a higher investment with motorised drilling and energy-powered pumps. In the latter case, constraints are linked to farmers' physical and financial access to mechanised technologies and energy. Hence, credit and capital become the most significant constraints faced by poor farmers. Also, low rural electrification in SSA tends to limit GWI, as

---

[19] http://www.unep.org/dewa/vitalwater/article69.html
[20] http://www.fao.org/nr/water/aquastat/main/indexfra.stm

diesel or petrol has a more expensive running cost than electricity. Finally, two other constraints have been identified: insecure land tenure and limited access to markets for cash crops.

1.2.5 A need for sustainable and regulated groundwater irrigation

As previously demonstrated, groundwater has the potential to be a reliable water source for irrigation if it is used wisely. However, there is a shared global concern about the socio-economic and environmental impact of groundwater use in agriculture (Madramootoo, 2012).

With many examples from Asia, Africa, and Europe, Shah et al. (2001) and De Stefano and Lopez-Gunn (2012) provide an overview of the impacts of unauthorised groundwater irrigation development (abstraction over the established limits or from unauthorised boreholes). This problem is related to the rapid and unplanned groundwater irrigation development which occurred in South Asia and North Africa at the end of the last century (Shah, 2009; Kuper et al., 2016). Regarding groundwater quantity, their findings indicate that the amount of the resource available for all users can decrease leading to a decline in the groundwater table. Also, the diminishing water flows from groundwater to wetlands or rivers can cause degradation (or disappearance) of riparian ecosystem habitats. Irrigation is only one of a number of groundwater uses which, not exclusively, include domestic and industrial water supply use and livestock watering. The development of groundwater irrigation should not interfere with other basic human or environmental water needs.

Regarding groundwater quality, intensive farming practices can result in groundwater contamination from fertilizers or pesticides, and abstraction in coastal areas can generate saline intrusion resulting in freshwater and saltwater mixing in wells and transitional surface water bodies. Salinization of groundwater (and soils) can also occur from extensive irrigation in dry climates: salts contained in the water used for irrigation accumulate in the soil profile after evaporation and re-dissolve either by the fluctuation of shallow groundwater or are leached down during irrigation, slowly increasing salinity in the groundwater (Barica, 1972). De Stefano and Lopez-Gunn (2012) also mentioned the indirect impact of unauthorised groundwater use on public finances. Many important water infrastructure projects are funded with public money, and the need to search for sustainable and alternative water resources to reduce groundwater over-exploitation could lead to substantial public investments. Finally, Tweed et al. (2018) highlight that groundwater irrigation can also impact changes in flow pathways resulting in deeper groundwater mixing with shallower groundwater. In this case, such a scenario can be beneficial since it reduces the nitrate concentration from agricultural practises in the shallower groundwater, but more generally deep/fossil groundwater can be high in salinity, and the artificial recharge from deeper groundwater can virtually hide the over-exploitation.

The decrease in the groundwater table, also called groundwater depletion, is one of the most significant present concerns. Several studies attempted to estimate groundwater depletion due to irrigation, but global estimates of groundwater depletion are uncertain ranging from 113 km^3/yr (Doll et al., 2014) to 362 km^3/yr (Pokhrel et al., 2012). Wada et al. (2010) estimated that groundwater depletion was 283 km^3/yr in 2000 and presented its worldwide distribution, indicating that groundwater depletion in Africa is limited and occurs in a few localised areas in Northern and Southern Africa (Figure 10). In this uncertain context, Wada et al. (2012) estimated that non-renewable groundwater abstraction contributed approximately 20% to the global gross irrigation water demand for the year 2000, with India (68 km^3/yr) being the most significant contributor followed by Pakistan (35 km^3/yr) and the United States (30 km^3/yr). A more recent study by Villholth et al. (unpublished) estimated that 14.5% of global irrigated agriculture production derives from depleting groundwater and that 32.6% of all groundwater-based agriculture production is based on unsustainable abstraction. In fact, the contribution of depleted groundwater to irrigation water demand has more than tripled over the period 1960-2000 (Wada et al., 2012). Cereals and sugar crops are the most unsustainable groundwater-irrigated crop production (Villholth et al., unpublished).

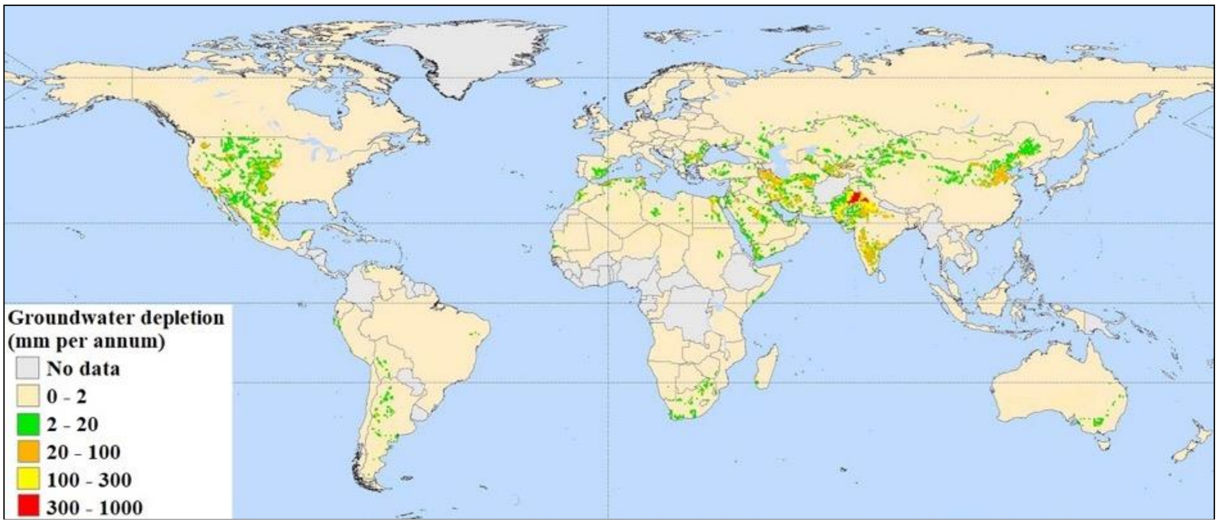


Figure 10: Groundwater depletion for the year 2000, expressed in mm per annum (Wada et al, 2010).

Degradation of the water quality is an essential issue that governmental institutions and farmers must face in many parts of the world, particularly when the domestic water supply, including drinking water, is from groundwater in the context of polluted surface water. For example, groundwater pollution due to fertilizers has become a significant problem in the heavily cultivated provinces of India and Northern China with nitrate levels rising above the national drinking water standard (Kajander et al. 2002). Similarly, high nitrate concentration is found in several Spanish aquifers because of poorly optimized irrigation and fertilization practises (Arauzo and Martínez-Bastida, 2015). Garduño and Foster (2010) described the Brazillian case of the Apodi Aquifer System where the rapid development of groundwater irrigation impacted the water quality of the more vulnerable limestone aquifer by leaching of nutrients and some pesticides from agriculture soils. In Korea, the government developed a program to reduce the seawater intrusion originating from groundwater withdrawal which caused an agricultural productivity decrease (Lee and Song, 2007). Narayan et al. (2007) showed that groundwater irrigation of sugarcane in the Burdekin Delta (Australia) is the main reason for saline intrusion while the control of seawater intrusion is attempted by replenishment of the groundwater through artificial recharge techniques. Moroccan farmers in the Chaouia region have adopted different strategies (from deeper boreholes to adaptive farming systems) to cope with seawater intrusion caused by intensive agricultural groundwater use since the 1970s (Berahmani et al., 2012).

Unfortunately, groundwater is an invisible resource, and its degradation in quantity or quality often takes significant time to be discovered if aquifers are not adequately monitored. Unplanned groundwater irrigation can result in the impoverishment of the groundwater resource and its sustainable potential for improving food security. Thus, there is a critical need to understand and monitor aquifer systems and to develop relevant and integrated policies at multiple levels when developing groundwater irrigation.

1.3 Research objective

From the previous sections, it is reasonable to assume that there is a significant opportunity for further developing GWI throughout the African continent, thereby increasing crop production and reducing food insecurity. This thesis focuses on the sustainable use of groundwater as the sole water source for irrigation. It considers the African nations' internal food production from groundwater irrigation as a factor for increasing country food availability and food security to reduce both poverty and undernourishment. Increased national food production lowers Africa's dependence on other regions and exposure to food prices from global market trade, thereby increasing farmer income. This thesis aims to locate areas where GWI can be developed sustainably in Africa, examining both quantitative and structural aspects of the GWI potential. As such, the overall objective of the thesis is to answer the following question:

Is there potential in Africa to develop more irrigated land with renewable groundwater?

The answer to this question will be determined based upon two research questions:

(1) *How much rainfed cropland in Africa can be irrigated with renewable groundwater and where is it located?*

(2) *Where in Africa is it worthwhile to develop this additional irrigation from renewable groundwater?*

Research question 1 refers to the total existing crop area in Africa where rainfall is insufficient to support optimal crop growth (this concept will be defined in section 2.1) and where renewable groundwater quantity is enough to irrigate the crop to attain this goal. Research question 2 refines these areas to take into consideration those factors which are conductive or constraining to GWI development in Africa.

The thesis is structured into four chapters:

- **Chapter 2** highlights previous studies and the existing knowledge gap in sustainable GWI development to emphasise the relevance of the study. The chapter presents the conceptual framework of the thesis.
- **Chapter 3** analyses the GWI potential in Africa. Through a quantitative hydrological approach, crop areas where groundwater can be used as a water source for sustainable irrigation are mapped and quantified.
- **Chapter 4** maps the GWI development in Africa. Biophysical and socio-economic factors are combined to identify those areas which are conducive to further GWI development within the identified GWI potential areas identified in Chapter 3.
- **Chapter 5** provides the general conclusion of the research and presents future research opportunities.

2 Mapping sustainable groundwater irrigation development potential in Africa

The previous chapter identifies GWI as a possible tool for increasing food production in Africa because there is a capacity for developing GWI through the continent, particularly in SSA. This chapter highlights and presents different studies on GWI potential to identify the gap in knowledge and to establish a relevant approach for mapping the potential for sustainable groundwater irrigation development. However, it is first necessary to explain the concept of sustainable irrigation water demand from groundwater as it is the critical element in determining the extent of crop areas that can be sustainably irrigated by groundwater.

2.1 The concept of sustainable irrigation from groundwater

Each crop needs to extract a specific amount of water for optimal growth. This requirement is referred to as the crop water demand, which represents the amount of water required 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). The crop water demand is specific to each crop in association with the climatic condition. The water naturally available for the crops is limited by rainfall and climate conditions (i.e., temperature, humidity, wind speed, and sunshine). Irrigation is then used to complement this natural water availability to reach the crop water demand. Thus, it is necessary to determine the volume of water abstracted to calculate the irrigation demand.

Figure 11 synthesizes the water cycle in the context of cropping, irrigation and groundwater recharge. The crop roots absorb water from the soil moisture, but most of this water escapes to the atmosphere as vapour by transpiration from the plant’s leaves and stem. Water on the leaves and stem of the plant and the soil surface escapes to the atmosphere by evaporation; this is called interception and soil evaporation, respectively. Falkenmark (1995) initially defined the concept of green water and blue water, with green water corresponding to the crop water demand and consisting of transpiration and evaporation, but there are several definitions for green water and blue water (Sood et al., 2014). This thesis defines green water as the water available for plants naturally and indirectly from the rainfall through soil moisture; this corresponds to transpiration only. The water that either runs off from the soil surface and infiltrates below the root zone to groundwater (i.e., groundwater recharge) is called blue water. This approach, effectively reducing precipitation by surface runoff, groundwater recharge, soil evaporation, and interception, gives a measure of readily available soil moisture for the plants, and ensures that the availability of water for the crops is not overestimated. This approach agrees with the green water definition by Savenije (2004) and the productive green water definition by Falkenmark and Rockström (2006), who define transpiration as the productive component of the green water, which is involved in biomass production in terrestrial ecosystems as opposed to the unproductive component attributable to soil evaporation.

Consequently, irrigation complements the lack of water naturally available to the crops to reach the water crop demand, and the irrigation water demand is determined according to Eq. 1:

$$\textit{Irrigation water demand} = \textit{crop water demand} - \textit{green water} \qquad (1)$$

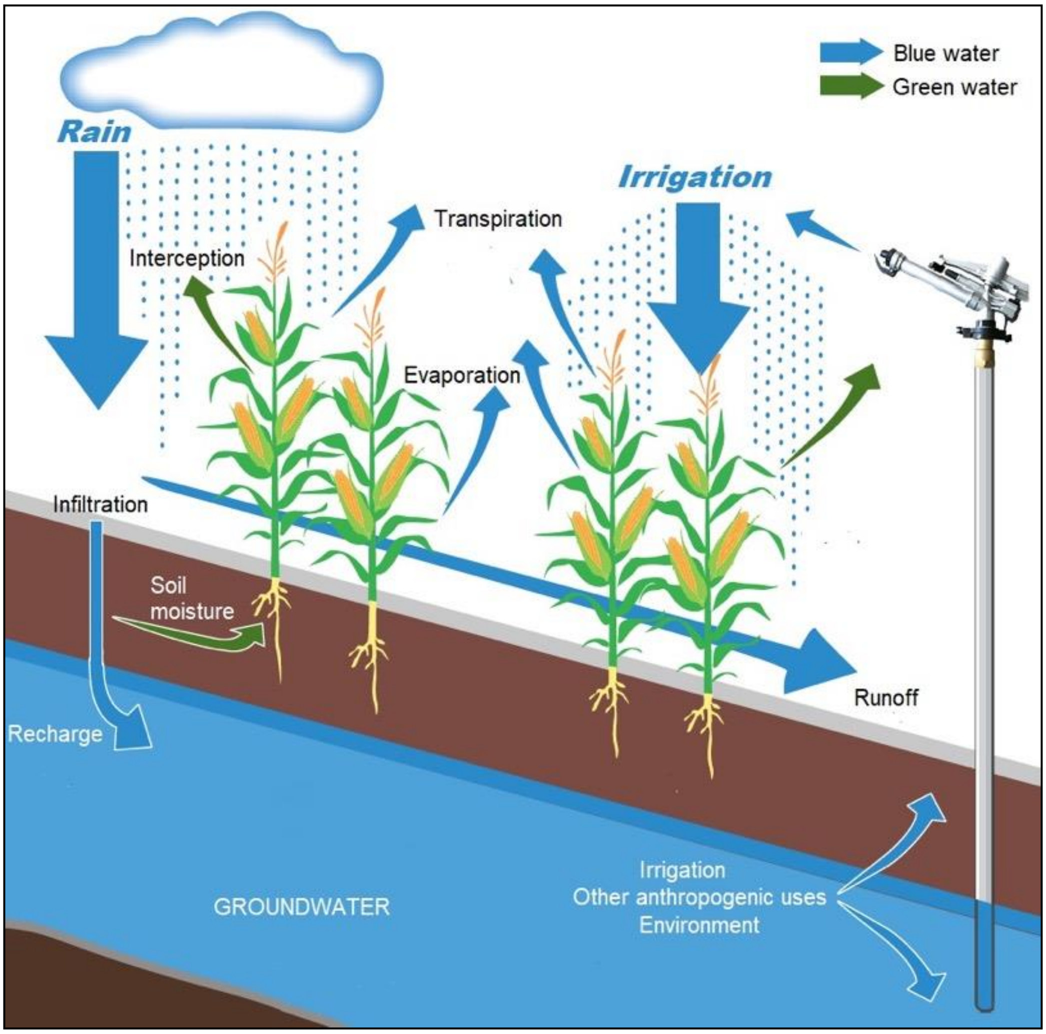


Figure 11: Water cycle in the context of cropping, irrigation and groundwater recharge, modified from IWMI (2007).

Eq. 1 is applicable independent of the water source used for irrigation. This thesis focuses on sustainable groundwater irrigation; “sustainable” is defined in this thesis as causing insignificant or no long-term damage to the environment. This means that the groundwater withdrawal for irrigation is from renewable groundwater (i.e., recharge) and must not compete with the other groundwater uses. Additional groundwater uses include abstraction for anthropogenic uses (i.e., drinking water and industrial processes), other agriculture use (i.e., livestock watering) and the groundwater environment requirement, which is the quantity of water coming from groundwater directly linked to the environment for maintaining ecosystems (i.e., river baseflow and groundwater influx to wetlands). Thus, sustainable irrigation from groundwater means that the groundwater withdrawals available for irrigation represent that portion of withdrawals from renewable groundwater that remains after satisfying all other groundwater uses.

2.2 Identification of the knowledge gap

Groundwater's potential as a water resource has been recognised and mapped in Africa at the local or national (Diabene and Gyamfi, 2014; Gumma and Pavelic, 2013; Villholth et al, 2013a), regional (MacDonald et al., 2000; Villholth et al., 2013b), and continental scale (MacDonald et al., 2012). Current irrigation with groundwater has also been mapped on a global scale by Siebert et al. (2010). However, most of the studies on GWI focused mainly on the impact of crop production on the underground water resource, the methods to reduce groundwater extraction through better crop water productivity, or the benefits of irrigation on crop production (Prihar et al., 2010; Siebert and Döll, 2010). This section presents the most relevant studies regarding irrigation potential in Africa to identify the knowledge gap in the potential of sustainable GWI. Table 2 summarizes the primary information from these studies.

FAO (1997) provided the first large study on irrigation potential in Africa, expressed as the area of land (ha) which is potentially irrigable. This study at river basin level considered the biophysical limitations for irrigation. Inside each hydrologic basin, the study determined the optimum soil suitability for surface irrigation, estimated the renewable water availability, and calculated the water crop requirements based on crop suitability for different agro-ecological zones. Soil suitability for irrigation is based on ten parameters (slope, drainage classes, texture, soil depth, surface stoniness, subsurface stoniness, calcium carbonate percentage, gypsum percentage, soil salinity, and soil alkalinity)[21]. from the FAO-UNESCO soil map of the world (FAD and UNESCO, 1974). Renewable water availability was globally estimated at the country level and was mainly based on surface water resources, except in arid countries where renewable groundwater already played an important role in irrigation development. By comparing the

---

[21] For this study, optimum soil and terrain suitability for surface irrigation corresponds to slope < 2%, well drained soil, silty clay loamy texture, soil depth > 100 cm, surface stoniness to 0%, subsurface stoniness < 40%, calcium carbonate < 30%, gypsium < 10%, salinity < 8 mmhos/mm and alkalinity < 15 ESP).

renewable water availability, the estimated crop requirements, and the soil and terrain characteristics, the study estimated the areas that could be equipped for irrigation. In 2005, the study received some minor updates (FAO, 2005). The results from the latest study assessed the potential irrigation development in Africa to be 42.5×10^6 ha, corresponding to 20.1% of the cultivated area or 5.7% of the cultivable land. The results present a semi-distributed map (one result per river basin), and there are no specific results for GWI as groundwater was integrated (partially) into the renewable water availability. Also, other water uses are not considered.

A few years later, Neumann et al. (2011) were the first to examine irrigation development at a worldwide scale using a multilevel modeling approach. The approach is based on a hierarchical linear model and comprises data from grid-cell data at a 5 arc-minute spatial resolution (about 10 km grid) and country data from multiple dataset sources. Grid-cell data includes existing current irrigation, slope, river discharge, humidity, evaporation, evapotranspiration, travel time to access market and population density. Non-distributed country data (one data per country) includes total renewable water resources, political stability, corruption control, government effectiveness, growth domestic product per capita as well as the level of democracy and autocracy. From the datasets, two models have been built. The first one uses only bio-physical information (model 1 includes slope, river discharge, humidity, evaporation, evapotranspiration) and the second one uses all datasets (model 2) to determine the potential for irrigated croplands which is then compared to existing irrigated croplands. This comparison highlights the areas where irrigation can likely be expanded. In Africa, results show that significant differences between model 1 and 2 occur only in Northern Africa and in the Sahel region, with model 2 showing higher probabilities for irrigation. These two regions are the only ones where areas with high likelihood of irrigation expansion have been identified. Since the approach does not take into consideration the crop water demand, results do not quantify the possible irrigation expansion, and groundwater is not considered in the method.

The same year, You et al. (2011) developed a distributed, economic-based estimate of irrigation potential for the continent and mapped the potential at a 5 arc-minute resolution (about 10 km grid). The estimate was based on biophysical and socio-economic parameters. Biophysical parameters included the local irrigated and non-irrigated crop yield from the Spatial Production Allocation Model (SPAM provides crop yield for twenty crops based on climatic conditions, crop growth period, slope, elevation and soil characteristics), the water resource availability (only runoff is considered) and topography. Socio-economic parameters were the maximum revenues from the potentially irrigable areas and the irrigation infrastructure costs. The comparison of the last two parameters determines the return on investment from the possible irrigation expansion. Small-scale and large-scale irrigation schemes differed in the calculation, as no water delivery cost is applied to small-scale irrigation because the water resource is assumed to be from local ponds, small reservoirs, rainwater harvesting, and groundwater. Hence, the study adds economic limitations to the biophysical constraints dataset. Results show that the irrigation potential in Africa is 23.6 x 10^6 ha (7.3 x 10^6 ha for small-scale irrigation and 16.3 x 10^6 ha for large-scale irrigation), which is lower than the figures from the previous FAO study since irrigation would not be economically viable everywhere. There are no specific results for GWI as groundwater was not integrated into the water availability.

More recently, Xie et al. (2014) estimated the potential for expanding smallholder irrigation in SSA by adopting a different but somewhat similar approach than You et al. (2011). They tried to reduce the resolution to 0.5 arc-minute, and developed scenarios based on four irrigation technologies: communal river diversions, small reservoirs, motor pumps, and treadle pumps, the last two integrating groundwater as a source for irrigation. First, the study estimated the irrigation potential using a multi-criteria GIS-analysis based on six parameters: soil type, topography, runoff, time to market, distance to surface water, and population density. Three to six parameters are used depending on the scenarios. Second, the areas with irrigation potential are refined using two predictive modeling tools to assess the economic and environmental condition of the area. The soil and water assessment tool (SWAT) model generates spatially disaggregated estimates of water availability, water consumption, and crop yields from biophysical parameter inputs such as climatic conditions, elevation, soil characteristics, land cover and crop cover while the dynamic research evaluation for management (DREAM) model measures economic returns of commodity production under a range of market conditions. Results indicate that the irrigation expansion potential is 20 million ha for communal river diversion, 22 million ha for small reservoir, 24 million ha for treadle pump (including 6 million ha from groundwater) and 30 million ha for motor pump (including 8 million ha for groundwater). The motor and treadle pump scenarios do not allow irrigation if the distance to surface water is greater than 500 m, limiting the potential considerably from GWI. Thus, GWI is only a partial estimate of the GWI in SSA and integrated to irrigation from surface water. Other water users are not considered in the study.

Droogers et al. (2012) developed an assessment of the irrigation potential of the Nile Basin. The study consisted of integrating five maps into one map at a 250 x 250 m resolution indicating the suitability of irrigation, expressed as a percentage of suitability for each cell. The five maps are built on several qualitative and quantitative parameters: (i) the terrain suitability corresponds to the terrain slope as slope is a crucial characteristic for assessing the irrigation potential[22]; (ii) the soil suitability for irrigation is based on the combination of six parameters from the Harmonized World Soil Database (HWSD) (drainage classes, water holding capacity, organic matter, texture, pH, and salinity)[23] and current land productivity based on the Normalized Difference Vegetation Index; (iii) the water availability combines two model results on water resources available from surface water, reservoir and groundwater, and irrigation water requirements based on the difference between reference and actual evapotranspiration; (iv) the distance to water sources combines the distance to surface water and the elevation above surface water; and (v) the accessibility to transportation combines distance to roads and cities. Results show that the overall irrigation potential (suitability > 0%) for the Nile Basin is about 51 x 10^6 ha, while 20 x 10^6 ha is suitable for irrigation development (suitability > 60%) in the six main sub-basins of the study. This study does not provide specific disaggregated results for GWI potential, and groundwater availability does not account for other groundwater use such as domestic use and groundwater-dependent ecosystems. Also, the methodology is unclear concerning the weighting of the different parameters.

These previous studies aimed to combine hydrological, biophysical and more socio-economic parameters to determine irrigation potential. However, neither study specified the irrigation potential for groundwater with Neumann et al. (2011) completely ignoring groundwater irrigation. The following studies focus specifically on the potential of GWI in Africa.

---

[22] steeper slopes are less suitable for irrigation even if hill-side irrigation exists

[23] best soils for irrigation correspond to soil with good drainage capacity, high water holding capacity, high carbon content, silt loam texture, pH close to neutral and very low salinity

Pavelic et al. (2013) estimated the GWI potential of 13 semi-arid countries in SSA. They used a relatively simple water balance approach to provide country or catchment scale estimates, respectively, of gross GWI potential regarding irrigable cropland, taking into consideration crop irrigation water needs and disregarding existing irrigation development. The groundwater available for irrigation was limited to renewable groundwater resources and groundwater demands for domestic, livestock, industrial uses, and environmental requirements are prioritised before irrigation. They determined the GWI potential of 13 countries to be in the range of 13.5 ± 6.0 x 10^6 ha, or between 0.1 – 3.9 x 10^6 ha per country. This approach does not reflect any distribution of the GWI potential inside the selected countries and does not account for socio-economic constraints to the development of GWI.

Forkuor et al. (2013) built on a previous study about groundwater potential (as a water source) to estimate the possible areas of groundwater development for agriculture in the North of Ghana. They refined the potential groundwater estimate by combining five parameters through a multi-criteria analysis approach at 1 km resolution scale to determine the accessibility of groundwater for agricultural purposes. The five parameters are recharge rate, regolith thickness, transmissivity, borehole success rate, and static water level. Results indicate that there is between 7.6 and 9.0 10^6 ha that could be developed with irrigation for agriculture. The study is at the local scale and does not consider socio-economic parameters or other groundwater uses.

The more recent study by Worqlul et al. (2017) focused on GWI in Ethiopia to determine the land suitability for GWI by combining biophysical and socio-economic parameters. The study compared the estimated land suitable for irrigation with the estimated groundwater availability and the irrigation requirement at a 1 km resolution scale. Parameters for determining the land suitability for irrigation include topography, soil characteristics, rainfall deficit, crop water requirement, land use, population density, and road proximity. Groundwater availability is mainly derived from groundwater depth and the borehole yield map of the British Geological Survey (MacDonald et al., 2012). Results indicate that, on average, groundwater can irrigate about 0.5 10^6 ha (8% of the land suitable for irrigation). However, this study is at a country scale and doesn’t account for other groundwater use such as domestic use and groundwater-dependent ecosystems.

Table 2: Summary of the information from relevant previous studies on irrigation potential and GWI potential in Africa.

Study	Irrigation Potential definition	Results	Scale (approximative resolution in meter)	Main input parameters (except water resource availability)	Consideration of the water resource availability				comments
					Surface water	Ground Water	Renew-ability	Other water users	
FAO (1997) FAO (2005)	Area (quantity)	42.5 10^6 ha	Africa (river basin)	Slope Soil characteristics Crop water requirement	yes	only in arid area	yes	No	
You et al. (2011)	Area (quantity)	23.6 10^6 ha	Africa (10 km)	Topography (slope and elevation) Soil characteristics Climatic conditions Crop water requirement Crop yield Return of investment	Yes (runoff)	No	Yes	No	Two scenarios: small irrigation and large irrigation
Xie et al. (2014)	Area (quantity)	From 20 to 30 10^6 ha	SSA (1 km)	Topography Soil characteristics Land cover Travel time to market Distance to SW Population density Climatic condition Crop water requirement Crop yield Return of investment	Yes (runoff)	Only nearby rivers	Yes	No	Focus on Smallholder and four scenarios for irrigation

Neuman et (2011)	Area (suitability)	No quantity	World (10 km)	Slope River discharge Climatic conditions Travel time to market Population density National economics and political indicators	yes	No	yes	No	Distributed data at grid cell level or country level
Droogers et al. (2012)	Area (quantity)	20 10^6 ha	Nile basin (250 m)	Slope Soil characteristics Land productivity Climatic conditions Crop water requirement Population density Distance to surface water Distance to market	Yes	Yes	Yes	No	
Pavelic et al. (2013)	Area (quantity)	13.5 10^6 ha	13 countries in SSA (country)	Renewable groundwater Crop water requirement	No	Yes	Yes	Yes	Water balance at country level
Forkuor et al. (2013)	Area (quantity)	From 7.6 and 9.0 106 ha	North of Ghana (1 km)	recharge rate regolith thickness transmissivity borehole success rate static water level	No	Yes	Yes	No	
Worqlul et al. (2017)	Area (quantity)	0.5 10^6 ha	Ethiopia (country)	Topography Soil characteristics Climatic conditions Crop water requirement Land use Population density Road proximity Groundwater characteristics	No	Yes	Yes	No	

Most of the studies of irrigation potential in Africa incorporate both surface and underground water resources or ignore groundwater. Specific studies of GWI potential in Africa are at a country scale or non-distributed. Hence, it appears that mapping of GWI potential in Africa has not been done, yet the need for quantified estimates of GWI potential is recognised at national (Ministry of Food and Agriculture, 2011[24]; Awulachew et al., 2010) and regional scales (MacDonald et al., 2012). Specific continental distributed studies on the location of GWI potential should allow for a better understanding of the role of groundwater in irrigation development (and food security) in African countries. The knowledge gap regarding mapping the potential of sustainable GWI development includes the need for geographically distributed and quantified estimates of the GWI potential at a continental scale (with high resolution), the need to take in consideration both renewable groundwater availability and other groundwater uses, and the need to consider the local biophysical and socio-economic environment.

2.3 Toward mapping sustainable groundwater irrigation development potential in Africa

It is recognised that Africa must undergo a complete agricultural revolution to successfully launch its economic transformation (Diao et al., 2010), and this revolution must come from increased food production and thus irrigation as well. Understanding the role that groundwater can potentially play in this transformation should better prepare farmers and countries to find appropriate solutions for agriculture processes and natural resource management to support climate change resilience and the reduction of undernourishment. Also, sustainable development is needed, since GWI can have a significant impact on groundwater-dependent populations and on the underground water resource itself. Depletion due to overdraft, water logging, and salinisation and pollution caused by agricultural, industrial, and other human activities are common issues in Asia (Shah et al., 2003).

---

[24] In Ghana’s National Irrigation Policy, groundwater irrigation falls under the category of “informal irrigation”.

From the identified knowledge gap, it appears that there is a scope to study the specific potential for sustainable GWI in Africa. It can be studied from a hydrological, quantitative point of view of the water resource by identifying the areas that the sole groundwater can sustainably irrigate, regardless of the other water sources or the constraints. It can also be studied from a biophysical and socio-economic point of view by identifying the conductivenss to the GWI development in Africa. Likewise, it can also be studied from an integrated approach. In fact, groundwater is generally a more reliable water source than surface water, specifically in the context of climate change. However, progress toward more significant and long-term groundwater benefits needs to be informed by estimates of the upper limits for sustainable development and the most appropriate geographic areas for development. Also, the broader continental approach will precisely locate areas inside the African countries where irrigation from renewable groundwater can play a role in food security and where government or donors can focus on more in-depth investigation and analysis (hydrogeology, environment, social equity, economic viability, investment access, institutions, and policies).

Thus, this thesis proposes to map Sustainable Groundwater Irrigation Development Potential (GIDP) in Africa and geographically identify and quantify areas at a 250 m resolution where GWI can be developed sustainably with the aim to promote sustainable GWI for reducing food insecurity in Africa. Figure 12 presents the conceptual framework of the thesis showing the two steps for mapping GIDP in Africa. The first step consists of mapping the Sustainable Groundwater Irrigation Resource Potential (GIRP) based on the irrigation water demand and sustainable groundwater availability for irrigation; this corresponds to the quantitative hydrological GWI potential approach of the GIDP and Chapter 3 of this thesis. The second step refines GIRP by taking in consideration the biophysical and socio-economic environment which can drive or limit the development of GWI and consists of creating a filter map of the Groundwater Irrigation Development Driver GIDD) over the GIRP. This corresponds to the semi-qualitative environmental approach of GIDP to Chapter 4 of this thesis, environmental relating to the biophysical and socio-economics surrounding of GWI.

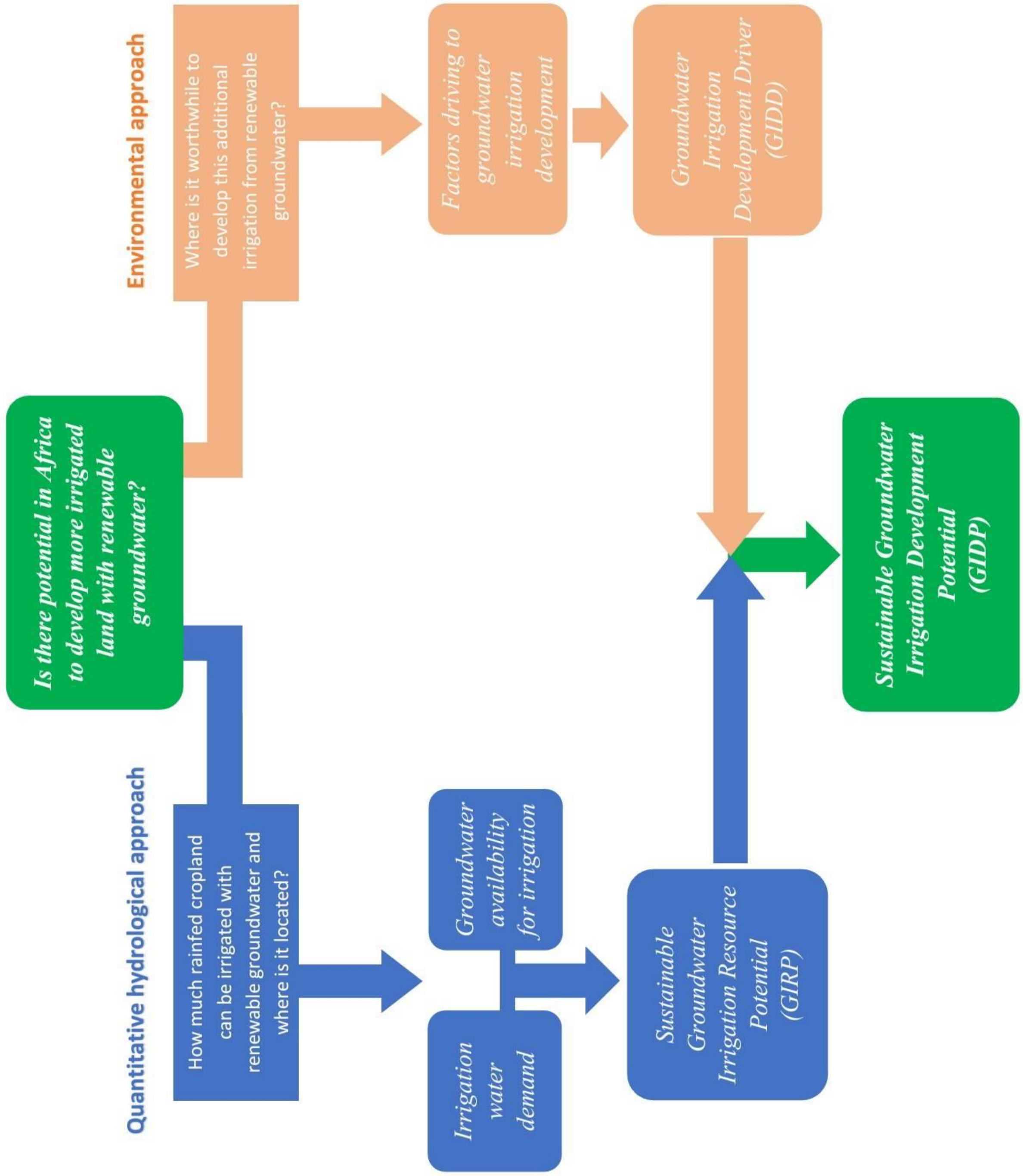


Figure 12: Conceptual framework for mapping sustainable groundwater irrigation development potential.

3 Mapping sustainable groundwater irrigation potential in Africa: a quantitative hydrological approach

Groundwater has been neglected as a water source for irrigation in Africa while it is recognized as a safe, reliable (especially during droughts) and affordable water source (Calow et al., 1997; Calow et al., 2010) and crop yield from groundwater irrigation is typically greater than from surface water irrigation (Burke et al., 1999). It exists in quantity throughout much of the continent, though not all of it is available for extraction or evenly distributed (MacDonald et al., 2012). Thus, groundwater has potential as a reliable water source for irrigation in Africa but the areas that can be developed with groundwater irrigation have not been identified over the continent. This chapter aims to estimate and map these areas by determining the groundwater irrigation potential through a quantitative hydrological approach, considering the availability of sustainable groundwater for irrigation, the crop water demand and the current cropland. It has been published as an article in Hydrology and Earth System Sciences (Feb. 26, 2015,) and is downloadable at http://www.hydrol-earth-syst-sci.net/19/1055/2015/hess-19-1055-2015.html. The article supplement corresponds to appendix 1 of this thesis and is downloadable at https://www.hydrol-earth-syst-sci.net/19/1055/2015/hess-19-1055-2015-supplement.pdf

To gain a better understanding of the published article, please note that the terminology differs slightly from this thesis. In this thesis, Groundwater Irrigation Resource Potential (GIRP) refers to the most constraining scenario of the Groundwater Irrigation Potential (GWIP) in the following article (Altchenko and Villholth, 2015), which imposes that 70% of the groundwater recharge returns to the environment. “Groundwater available for irrigation” in the thesis refers to “GW available” in this article.

Hydrol. Earth Syst. Sci., 19, 1055–1067, 2015
www.hydrol-earth-syst-sci.net/19/1055/2015/
doi:10.5194/hess-19-1055-2015
© Author(s) 2015. CC Attribution 3.0 License.

Hydrology and Earth System Sciences
Open Access

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

Y. Altchenko[1,2,3] **and K. G. Villholth**[1]

[1]International Water Management Institute, Pretoria, South Africa
[2]Ministère de l'Agriculture, de l'Agroalimentaire et de la Forêt, Paris, France
[3]Laboratoire METIS, UMR 7619 UPMC/CNRS, Université Pierre et Marie Curie, Paris, France

Correspondence to: Y. Altchenko (y.altchenko@cgiar.org)

Received: 15 April 2014 – Published in Hydrol. Earth Syst. Sci. Discuss.: 10 June 2014
Revised: 3 October 2014 – Accepted: 29 October 2014 – Published: 26 February 2015

Abstract. Groundwater provides an important buffer to climate variability in Africa. Yet, groundwater irrigation contributes only a relatively small share of cultivated land, approximately 1 % (about 2×10^6 hectares) as compared to 14 % in Asia. While groundwater is over-exploited for irrigation in many parts in Asia, previous assessments indicate an underutilized 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 hydrological data, allocating only that fraction of groundwater recharge that is in excess after satisfying other present human needs and environmental requirements, while disregarding 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, mainly reflecting recharge patterns and presence or absence of cultivated cropland. Results further show that average annual renewable groundwater availability for irrigation ranges from 692 to 1644 km^3 depending on scenario. The total area of cropland irrigable with renewable groundwater ranges from 44.6 to 105.3×10^6 ha, corresponding to 20.5 to 48.6 % of the cropland over the continent. In particular, significant potential exists in the semi-arid Sahel and eastern African regions which could support poverty alleviation if developed sustainably and equitably. 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.

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 re-

---

[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, and 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, and so forth.

Published by Copernicus Publications on behalf of the European Geosciences Union.

gional plans, groundwater is increasingly included as a viable and suitable supplementary or sole source 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[3] (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 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 (including ponds, small reservoirs, rainwater harvesting, and groundwater) in Africa to be 0.3 to 16×10^6 ha based on a continental distributed mainly economic multi-criteria analysis at a 5 min. resolution. Pavelic et al. (2012, 2013) afforded a relatively simple water balance approach to provide country or catchment scale estimates, respectively, 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°. The concept of the approach is to map crop area that can be irrigated with locally renewable groundwater resources at a continental and distributed scale. 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 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 × 50 km) to be homogeneous and independent of other cells, i.e. no lateral groundwater or irrigation water 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 (Supplement):

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

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:

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

The gross irrigation water demand $[L\,T^{-1}]$, which represents the groundwater abstraction needed to satisfy the deficit rain-

---

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

[3] Cultivated land and cropland are here used interchangeably, to mean the combined arable land area and the area under permanent crops (http://www.fao.org/nr/water/aquastat/data/glossary/search.html?lang=en).

fall and the irrigation losses, is determined by

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

The crop water demand [$\mathrm{L\ T^{-1}}$], which represent the monthly 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), is determined by:

$$\text{Crop Water Demand}_j = K_\mathrm{c} \times E_{0,\mathrm{max}_j}. \quad (4)$$

The equation parameters are given as follows:

- $E_{0,\mathrm{max}}$ [L] is the maximum reference evapotranspiration for each calendar month.
- K_c [–] is the crop coefficient.
- Green Water [$\mathrm{L\,T^{-1}}$] is the water available for plants naturally and indirectly from the rainfall through soil moisture.
- % of Area [–] is the areal fraction of a specific crop relative to the total crop area within a grid cell.
- n [–] is the number of crops grown within the grid cell.
- m [–] is the number of months of the year (12).
- 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.
- GW Recharge [$\mathrm{L^3\,T^{-1}}$] is the net groundwater recharge. It corresponds to the total quantity of water from rainfall which reaches the aquifer as diffuse recharge. Return flows from surface water irrigation and other forms of artificial recharge as well as focused or induced recharge from water surface bodies are disregarded.
- Human GW Demand [$\mathrm{L^3\,T^{-1}}$] 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. [$\mathrm{L^3\,T^{-1}}$] 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 considering 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; Wada 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 (i.e. natural vegetation and rainfed crops) was used (Van Beek et al., 2011). This conservative approach, effectively reducing precipitation for surface runoff, percolation, soil evaporation and interception, gives a measure of easily available soil moisture for the plants, and ensures that the availability of water for the crops is not overestimated. This approach is in agreement with the green water definition by Savenije (2004) and the productive green water definition by Falkenmark and Rockström (2006), who define transpiration as the productive component of the green water, which is involved in biomass production in terrestrial ecosystems as opposed to the unproductive part attributable to soil evaporation (Supplement).

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 have been used (Monfreda et al., 2008; Ramaunkutty 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

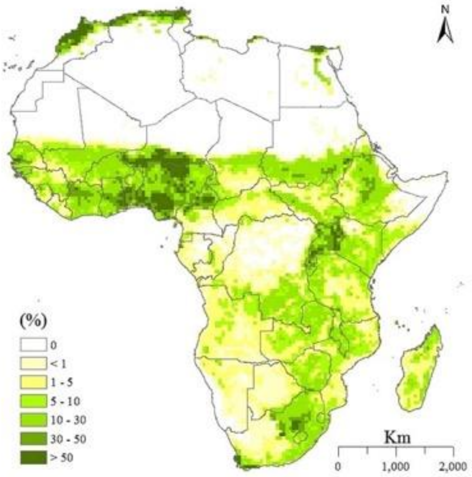


Figure 1. Proportion of cropland per cell (0.5 x 0.5 degree) in 2000 (Ramankutty et al., 2008).

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

Type of crop	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 %

(165.7×10^6 ha) over the continent, were considered (Table 1).

These include: cereals, oil crops, 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. It is assumed that the cropping pattern is not influenced by introduction of groundwater. While it is known that smallholder GWI may preferentially be applied to higher value crops (like vegetables) in SSA (Villholth, 2013) and that the dominant crops in irrigated and rainfed agriculture differ from region to region in Africa (Portmann et al., 2010), no data on the larger scale and distributed impact of crop pattern change as a result of GWI exist.

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 ensure 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[4] 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 year-round cropping and an annual cropping rotation.

The monthly crop water demand for each crop group is determined by Eq. (4), using the maximum monthly reference evapotranspiration for each calendar month over the period 1960–2000 and crop coefficient (K_c) as determined in the Supplement. Growth periods and corresponding Kc values for the various crops are extracted from the literature (FAO, 1992, 1986) and are assumed to be constant over the 41-year period while the reference evapotranspiration data are extracted from inputs to the PCR-GLOBWB global hydrological model. 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 has been applied, unless the difference between them is equal to or more than 0.05 and 0.1, in which case the larger coefficient is reduced by 0.01 or 0.02, respectively. 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 canals) 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 to be less efficient

---

[4] http://www.fao.org/agriculture/seed/cropcalendar/welcome.do (last access: 31 March 2014).

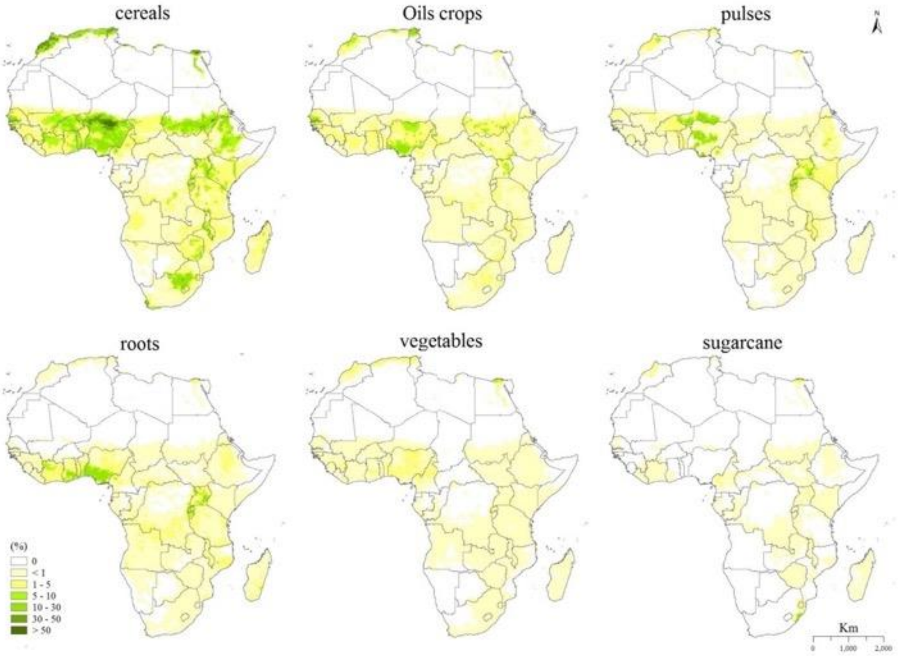


Figure 2. Proportion of crop group area per cell (0.5° × 0.5°) cultivated in 2000 of the six largest crop groups (adapted from Ramankutty et al., 2008).

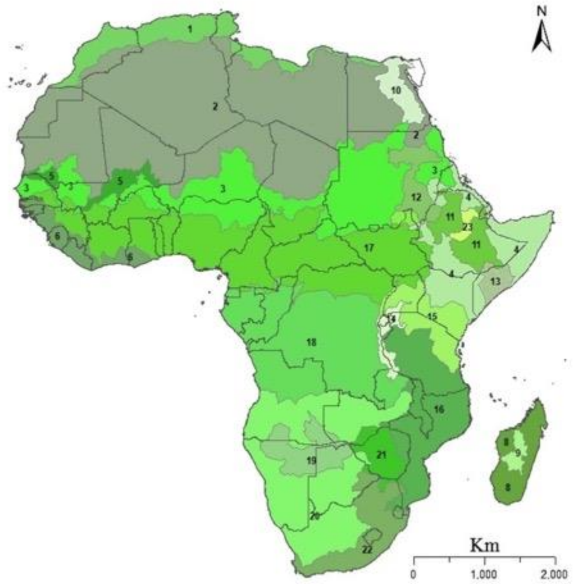


Figure 3. Delineation of the 23 irrigation cropping pattern zones in Africa (based on FAO, 1997; http://www.fao.org/geonetwork/srv/en/main.home, last access: 1 April 2014).

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: with environmental groundwater requirements representing 70 % (Scenario 1), 50 % (Scenario 2), and 30 % (Scenario 3) of the recharge, respectively over the continent (Pavelic et al., 2013).

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 & 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

4 Calculation of groundwater irrigation potential

The GWIP (Eq. 1) is calculated using the maximum annual estimate of irrigation water demand (Irrig. Water Demand) over the 1960–2000 period for each cell. Hence, a conservative estimate of the irrigation potential is obtained. However, rather than equally using the maximum values of groundwater availability (GW Available), a constant averaged annual value of this parameter was used. 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 of crop water demand for the individual crop groups within each cell, after reducing by available green water for each particular month. The share of each crop group within the crop group area is accounted for (% 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 crops in the crop group.

5 Results

The 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). It also reflects the green water availability, which is

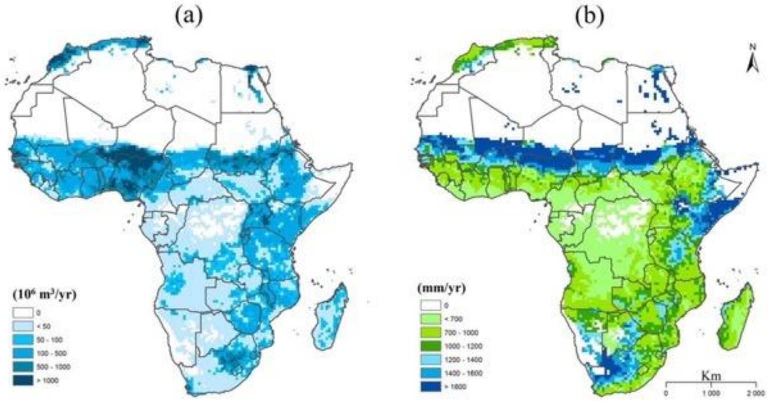


Figure 4. Estimated average net irrigation water demand (1960–2000) for the cropland in Fig. 1: **(a)** expressed in $10^6\,\mathrm{m}^3\,\mathrm{year}^{-1}\,\mathrm{cell}^{-1}$ ($0.5° \times 0.5°$) and **(b)** in $\mathrm{mm\,year}^{-1}$.

higher in the equatorial regions, except in East Africa (Supplement).

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 $1644\,\mathrm{km}^3\,\mathrm{year}^{-1}$ (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 GWI 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 unexploited opportunities for groundwater development for agriculture, with up to all cropland, and sometimes more, being irrigable from renewable groundwater. This benefit accrues from mostly supplementary GWI in the wet season as well as mostly full GWI in the dry season. The maps also indicate that relatively large disparities in GWIP exist within individual countries, e.g. Ethiopia, Mozambique, Angola and Tanzania. 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 44.6×10^6 ha to 105.3×10^6 ha for the three scenarios, corresponding to 20.5 to 48.5 % of the cropland.

The GWIP for the 13 countries estimated by Pavelic et al. (2013) (13.5×10^6 ha) is here calculated to 17.1×10^6 ha, showing good correspondence between the methods, though the present method does indicate the distributed extent of GWIP across the countries and for the whole continent. In Table 4, 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 20 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. Comparing the GWIP with the overall irrigation potential of 42.5×10^6 ha estimated by FAO (2005), it is clear that groundwater can play a significant role in food production and food security in large parts of Africa. While in such comparison, figures for irrigation potential may not be simply additive due to overlap of the resources and lack of cropland or other constraints, it is clear that opportunities exist in the concurrent development of both sources and some benefits are achievable in planning schemes that are conjunctive (Evans et al., 2012).

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

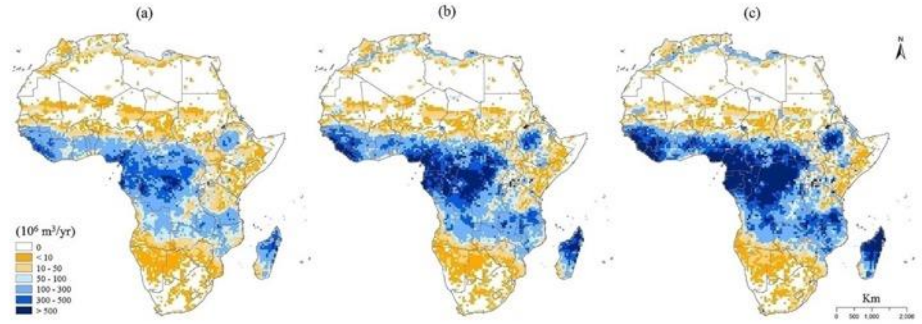


Figure 5. Average groundwater availability for irrigation (1960–2000), expressed in $10^6\,\mathrm{m}^3\,\mathrm{year}^{-1}\,\mathrm{cell}^{-1}$ ($0.5° \times 0.5°$), for various levels of environmental groundwater requirements as a fraction of recharge: **(a)** Scenario 1: 70 %, **(b)** Scenario 2: 50 %, **(c)** Scenario 3: 30 %.

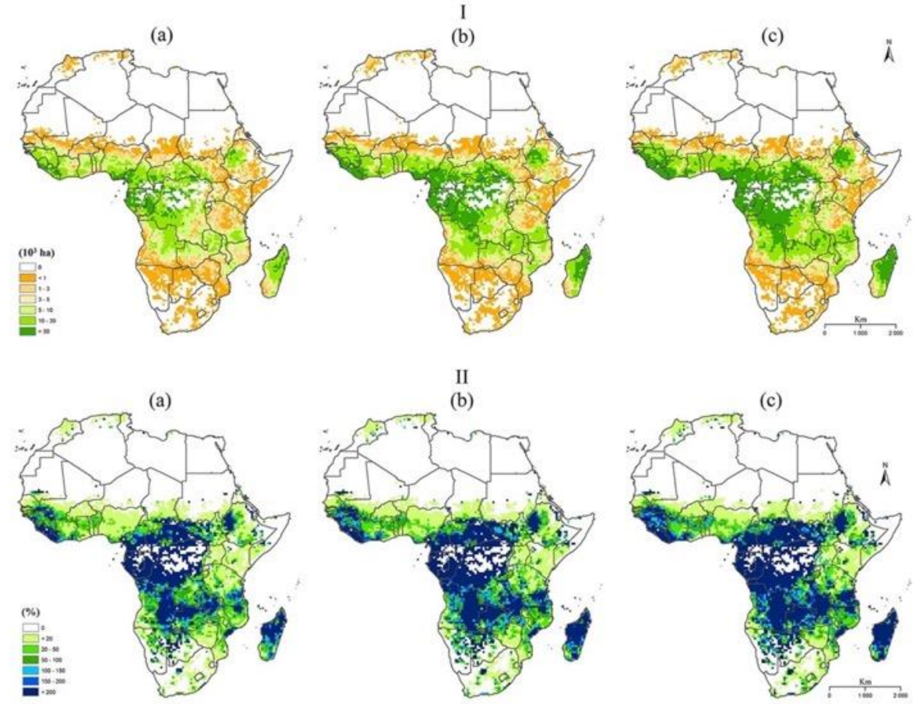


Figure 6. (I) Total area irrigable with groundwater inside a cell ($0.5° \times 0.5°$) in 10^3 ha and (II) proportion of cropland irrigable with groundwater, for various levels of environmental groundwater requirements as a fraction of recharge: **(a)** Scenario 1: 70 %, **(b)** Scenario 2: 50 %, **(c)**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

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 non-red areas versus 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 limited 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 northeastern South Africa and southeastern North Sudan (data not

Table 4. Gross groundwater irrigation potential and cultivated area per country in Africa.

	Area of cropland irrigable with groundwater[a] (10^3 ha)			Siebert et al. (2010)	FAO – AQUASTAT[b]
	Scenario (Percentage of groundwater for environmental requirements)			Area equipped for irrigation irrigated with groundwater (10^3 ha)	Cultivated land (10^3 ha)
	1 (30 %)	2 (50 %)	3 (70 %)		
Algeria	140	94	49	362.1	8465
Angola	7032	5016	3001	16.0	5190
Benin	518	368	218	2.2	3150
Botswana	66	46	27	0.7	287
Burkina Faso	268	188	108	3.0	6070
Burundi	214	149	84	0.0	1450
Cameroon	7019	5005	2990	1.0	7750
Central African Republic	6961	4969	2978	0.0	1880
Chad	566	401	237	6.0	4932
Côte d'Ivoire	2920	2078	1236	0.0	7400
Democratic Republic of Congo	23 060	16 450	9840	0.0	7810
Djibouti	5	3	2	1.0	2
Egypt	2	2	1	331.9	3612
Equatorial Guinea	634	453	271	0.0	180
Eritrea	10	7	4	16.2	692
Ethiopia	4336	3064	1793	2.6	16 488
Gabon	5884	4202	2520	0.0	495
Gambia	24	17	10	0.0	445
Ghana	1426	1010	594	12.0	7400
Guinea	2751	1962	1172	0.5	3700
Guinea-Bissau	176	125	75	4.9	550
Kenya	512	355	199	1.0	6130
Lesotho	21	15	8	0.1	285
Liberia	2238	1597	956	0.0	710
Libya	26	18	10	464.0	2055
Madagascar	6753	4814	2875	0.0	4110
Malawi	640	454	268	0.0	3885
Mali	787	559	331	1.0	7011
Mauritania	52	37	22	4.8	411
Morocco	145	97	49	677.2	9403
Mozambique	2171	1546	921	0.6	5950
Namibia	98	70	41	1.6	809
Niger	19	12	6	1.4	16 000
Nigeria	6287	4446	2606	66.8	41 700
Republic of Congo	7420	5295	3170	0.0	600
Rwanda	148	102	56	0.1	1432
Senegal	382	271	160	10.2	3415
Sierra Leone	1551	1107	662	0.2	1897
Somalia	51	35	20	10.0	1129
South Africa	270	181	95	127.3	12 413
South Sudan	3042	2164	1286	0.2	2760[c]
Sudan	429	299	169	69.0	13 893[c]
Swaziland	21	15	8	1.0	190
Tanzania	3007	2135	1263	17.5	16 650
Togo	300	213	126	0.1	2850
Tunisia	26	17	9	257.0	5249
Uganda	571	399	228	0.1	9150
Western Sahara	0	0	0	0.0	4[c]
Zambia	3952	2818	1684	6.7	3836
Zimbabwe	370	259	148	20.0	4100

[a] 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);
[b] http://www.fao.org/nr/water/aquastat/countries_regions/index.stm; [c] estimated.

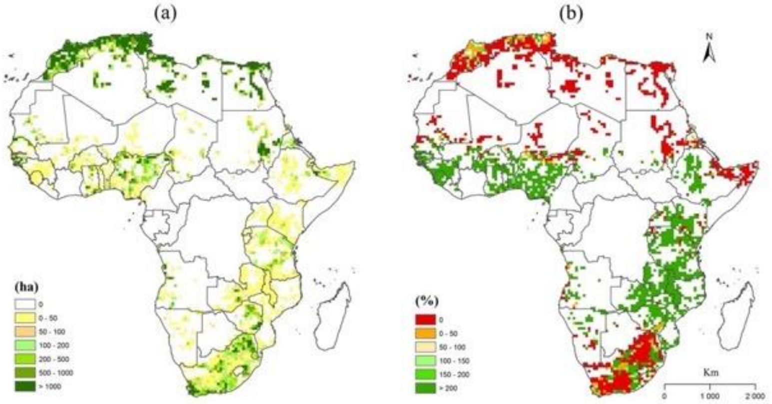


Figure 7. (a) Area irrigated with groundwater in 2005 expressed in ha. per cell adapted from Siebert et al. (2010) and **(b)** groundwater irrigation potential for Scenario 2 (the environmental groundwater requirements represent 50 % of the recharge) for the year 2000 expressed as the percentage of the area irrigated with groundwater in 2005.

Table 5. 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 accessed: 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).

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 5 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 data set. 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 needs 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

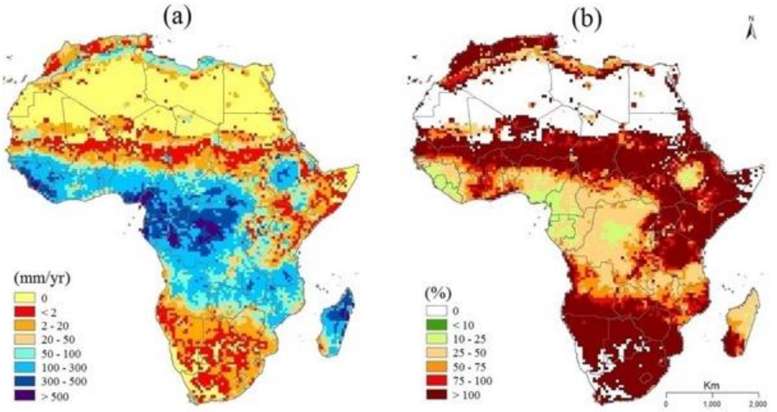


Figure 8. Average annual recharge (mm year^{-1}) and **(b)** its coefficient of variation (%), both over the period 1960–2000 (data from Van Beek et al., 2011).

Table 6. 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.

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 the 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 6) (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 of the same order of magnitude as the effect of the temporal variability of recharge.

6.2 Limitations of approach

The water balance approach considers locally renewable groundwater 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 hectare for landholdings larger than 1 ha, over the continent and the gross irrigation water demand per year varying between 235 and 3000 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 0.3 to 4.3 $\text{L}\,\text{s}^{-1}$. 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.

The GWIP was conceived strictly in terms of the quantitative availability of renewable groundwater. Possible constraints related to hydrogeology as well as water quality and socioeconomic conditions, such as infrastructure (roads, markets, energy/electricity) or intuitional/farmer capacities may further reduce this potential or hamper its realization as will be further analysed in a companion paper. Rapid assessment of borehole yields indicated a possible limitation due to the hydrogeological transmitting properties in certain regions.

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. Likewise, historic and potential future changes in cropping patterns and irrigation efficiencies have not been considered though they could significantly enhance the groundwater availability, through increasing the green water availability (by shifting the unproductive part to productive), and hence the potential for irrigation. In essence, the method is a snapshot continental distributed view of present or most recent GWIP, based on averaged hydrological conditions and best available most recent coherent data sets. However, the influence of cropping choice was clearly demonstrated in Pavelic et al. (2013). They showed that going from a 1000 mm year^{-1} irrigation demand to a 100 mm year^{-1} crop, everything else being equal, entailed an order of magnitude higher 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 44.6×10^6 ha and 105.3×10^6 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, from recharge from larger rivers like the Nile, or return flows from surface water schemes, while the rest of the continent (except for the Sahara region) still has appreciable potential, especially and most relevantly for smallholder and less intensive GWI in the semi-arid Sahel and east Africa regions. This could significantly increase the food production and productivity in the region from a reliable and renewable resource.

The Supplement related to this article is available online at doi:10.5194/hess-19-1055-2015-supplement.

Acknowledgements. Rens Van Beek, Geosciences – Utrecht University, kindly provided data from the PCR-GLOBWB model. Agnès Ducharne, Laboratoire METIS – Université Pierre et Marie Curie – Paris, provided critical view, specifically on Crop Water Demand. The work has been partially funded by the French Ministry of Agriculture and by USAID (Enhanced Regional Food Security through Increased Agricultural Productivity to Sustainably Reduce Hunger project of the USAID Southern Africa Feed The Future (FTF) programme (2012–2013)). It was also supported by CGIAR Strategic Research Program on Water, Land and Ecosystems (WLE).

Edited by: M. Vanclooster

References

Adelana, S. M. A. and MacDonald, A. M.: Groundwater research issues in Africa, in: Applied Groundwater Studies in Africa, edited by: Adelana, S. M. A. and MacDonald, A. M., IAH Selected Papers on Hydrogeology, no. 13, Ch. 1, CRC Press, Taylor & Francis Group, London, UK, 507 pp., 2008.

Awulachew, S. B., Erkossa, T., and Namara, R. E.: Irrigation Potential in Ethiopia – Constraints and Opportunities for Enhancing the System, International Water Management Institute, available at: http://www.ata.gov.et/wp-content/uploads/Ethiopia-Irrigation-Diagnostic-July-2010.pdf (last access: 20 May 2014), 59 pp., 2010.

CAADP (Comprehensive African Agriculture Development Programme): Sustainable Land and Water Management, The CAADP Pillar I Framework, available at: http://www.caadp.net/pdf/CAADPPillar1Framework.pdf (last access: 21 May 2014), 76 pp., 2009.

Döll, P. and Fiedler, K.: Global-scale modeling of groundwater recharge, Hydrol. Earth Syst. Sci., 12, 863–885, doi:10.5194/hess-12-863-2008, 2008.

Evans, W. R., Evans, R. S., and Holland, G. F.: Conjunctive use and management of groundwater and surface water within existing irrigation commands: the need for a new focus on an old paradigm. Thematic Paper 2. Groundwater Governance: A Global Framework for Country Action, GEF ID 3726, 48 pp, 2012.

Falkenmark, M. and Rockström, J.: The new blue and green water paradigm: Breaking new ground for water resources planning and management, J. Water Resour. Plann. Manage., 132, 129–132, 2006.

FAO: Irrigation Water Management: Irrigation Water Need, Training Manual no. 3, edited by: Brouwer, C. and Heibloem, M., Food and Agriculture Organization of United Nations, Rome, Italy, 102 pp., 1986.

FAO: Irrigation Water Management: Irrigation Scheduling, Training Manual no. 4, edited by: Brouwer, C., Prins, K., and Heibloem, M., Food and Agriculture Organization of United Nations, Rome, Italy, Land and Water Development Division, 66 pp., 1989.

FAO: Crop Water Requirements, FAO Irrigation and Drainage Paper no. 24, edited by: Doorenbos, J., Pruitt, 5 W. O., Aboukhaled, A., Damagnez, J., Dastane, N. G., Van den Berg, C., Rijtema, P. E., Ashford, O. M., and Frere, M., Food and Agriculture Organization of United Nations, Land and Water Development Division, Rome, Italy, 144 pp., 1992.

4 Mapping sustainable groundwater irrigation development potential in Africa: a development perspective

The previous chapter estimated the extent and distribution of groundwater irrigation potential across the African continent at a 0.5-degree resolution (about 50 km x 50 km) using a quantitative hydrological approach. It considers the sustainable availability of groundwater for irrigation as well as long-term climatic conditions for the estimation of crop irrigation needs, but it disregards socioeconomic and biophysical constraints on groundwater irrigation development. When 70% of the recharge is allocated to the environment, results indicate that a total area of 44.6 x 10^6 ha can be irrigated with groundwater. This estimate, called sustainable groundwater irrigation potential (GIRP), includes existing groundwater irrigation. A comparison with existing groundwater irrigation reveals that it has been developed mostly in North Africa and Southern Africa where potential is limited and where irrigation is from non-renewable groundwater and recharge from large rivers (e.g., the Nile river) or surface water schemes. The rest of the continent shows considerable potential except in the Sahara Desert. There is untapped potential in Eastern Africa and the Sahel region that could significantly improve food security in Africa.

The mapping of GIRP does not consider any factors which constrain or are conducive to development of groundwater irrigation except the quantity of renewable groundwater and the crop water demand. This chapter integrates additional factors that drive the development of groundwater irrigation by adding environmental conduciveness to the development potential. This chapter aims first to locate and rank into classes of conduciveness these areas inside countries where groundwater irrigation development could be developed. Second, the areas which are worthwhile to develop with sustainable groundwater irrigation are located and quantified.

4.1 Linking sustainable groundwater irrigation potential to sustainable groundwater irrigation development potential

The water balance approach for mapping the GIRP was developed strictly by the quantitative availability of renewable groundwater. It reflects locally renewable groundwater availability as the primary controlling parameter and assumes non-limiting conditions of other fundamental physical properties, e.g., soil and water quality, terrain slope and groundwater accessibility (as determined by the depth of the usable aquifer, storage available for recharge, and well yields) for the implementation of groundwater irrigation. However, possible constraints related to hydrogeology as well as water quality and socioeconomic conditions, such as infrastructure (roads, markets, energy/electricity) or institutional /farmer capacities may further reduce this potential or hamper its realization. Several articles attempt to link both biophysical and socio-economic constraints for determining the irrigation potential at local (Wale et al., 2013), national, regional (Droogers et al., 2012) and worldwide scales. (Neumann et al., 2011). However, only a recent study by Worqlul et al. (2017) focuses explicitly on groundwater, but the local scale does not provide useful information for improving inter-regional and intra-country water management and food production heterogeneity. This chapter proposes to link GIRP to GIDP through the determination of the groundwater irrigation development driver (GIDD). The following section of this chapter corresponds to an article which is planned to be submitted to Hydrogeology Journal.

4.2 Mapping sustainable groundwater irrigation development potential in Africa

4.2.1 Introduction

Groundwater is a widely accessible resource and is often of good quality if it is sustainably abstracted (ADB, 2013). Groundwater is a seasonally reliable water source, making it a critical element in adapting to climate change (Calow et al., 2010). The groundwater resource is also inexpensive to develop (especially from shallow aquifers), compared to surface reservoirs, when it is located close to the demand (UNEP, 1996). Since the 1970s, groundwater has aided millions of Asian farmers in overcoming food shortages because small-scale groundwater irrigation leads to improved equity of access to irrigation (ADB, 2013)

In comparison to Asia, Africa's current groundwater irrigation (GWI) is limited, covering slightly more than 2×10^6 ha in 2005, as compared to 38×10^6 ha in Asia, and irrigation development in sub-Saharan Africa has been slow (Siebert et al., 2015), although there are indications of increasing development in specific regions (Villholth, 2013). About one-quarter of the Sub-Saharan African (SSA) population and 20% of the total population of Africa remains chronically hungry (FAO et al., 2014). Thus, in addition to reducing exposure to the risks associated with droughts, the use of groundwater for expanding irrigation in Africa represents a means to improve food security, livelihoods and rural development in general.

African continental plans recognise irrigation development as a tool for the mitigation of poverty and hunger (NEPAD et al., 2009; AU, 2014), and specific national policies and strategies highlight the importance of groundwater irrigation in Ethiopia (Ministry of Finance and Economic Development, 2010), Ghana (Ministry of Food and Agriculture, 2011), Malawi (Ministry of Irrigation and Water Development, 2005), South Africa (Department of Water Affairs, 2013) and Zambia (Ministry of Agriculture, 2004). Barriers to the expansion of groundwater-based irrigation in Africa include a lack of knowledge of the resource, as well as development constraints regarding infrastructure development and financing options for smallholders, particularly in SSA (Villholth, 2013). Altchenko and Villholth (2015) mapped the groundwater resource potential for irrigation using a hydrological, quantitative approach based on annual groundwater balances over a 41-year period. Their continent-wide analysis (0.5-degree spatial resolution) considered the water resource available for irrigation as the excess long-term average groundwater recharge above current human needs and environmental requirements, without regard for socioeconomic and ecological factors that influence access to and development of the resource. Due to the considerable uncertainty of environmental requirements for groundwater, three scenarios were developed, allocating 30%, 50% and 70% of the total recharge to the environment. The study aggregated dominant crops into six groups (cereal, pulse, root, oil, vegetable and sugarcane) with prevalent crop rotations and associated irrigation requirements (i.e., the additional water needed by the crop after naturally available water from rain and soil moisture were accounted for) applied in a zonal approach to convert recharge surplus into potentially irrigable cropland areas. Irrigation requirements were based on climatic conditions and crop group-specific water requirements needed to achieve optimal growth. For the current study, groundwater irrigation resource potential is defined according to the most constraining scenario of Altchenko and Villholth (2015) which requires that 70% of the groundwater recharge be allocated to the environment, herein referred to as sustainable groundwater irrigation resource potential (GIRP) and expressed in terms of areas irrigable with renewable groundwater.

While several studies qualitatively mapped groundwater availability or vulnerability on national (MacDonald et al., 2001) or regional scales (Villholth et al., 2013b), a combined continental mapping of the biophysical and socio-economic driving factors influencing groundwater irrigation development does not exist. However, there are several studies at the regional or country scale that estimate irrigation development potential from surface water and groundwater.

For example, Droogers et al. (2012) developed an assessment at a 250 x 250 m resolution of the irrigation development potential of the Nile Basin using surface and groundwater as the source for irrigation. The study consisted of integrating five maps into one map indicating the suitability for irrigation, expressed as a percentage of suitability for each cell. The five maps, each built from several qualitative and quantitative parameters, include terrain suitability (slope), soil suitability (soil characteristics and current land productivity), water availability (the water resource available and irrigation water requirements), the distance to water sources, and access to transportation. The results indicate that the overall irrigation potential (suitability > 0%) for the Nile Basin is about 51 x 10^6 ha, while 20 x 10^6 ha is suitable for irrigation development (suitability > 60%).

Another example is Xie et al. (2014), who estimated the potential irrigation development for expanding smallholder irrigation in SSA at 1 km resolution. First, the study estimated the irrigation potential using a multi-criteria GIS-analysis based on four irrigation technologies (communal river diversion, small reservoir, motor pump, and treadle pump) and six parameters (soil type, topography, runoff, time to market, distance to surface water, and population density). Three to six parameters were used depending upon the scenario. Second, the areas with irrigation potential were refined using biophysical and economic conditions (water availability, water consumption, crop yields, returns of commodity production). The results indicate that the irrigation expansion potential varies from 20 to 30 million ha depending on the specific irrigation technology. Groundwater is accounted for in water availability for the motor and treadle pump scenario only if the distance to surface water is less than 500 m, limiting the potential for GWI considerably.

It is important to note that none of these studies focused on the irrigation development potential from groundwater, since surface water is the dominant irrigation source, though it is possible to utilize groundwater for irrigation purposes irrespective of surface water sources.

A recent study in Ethiopia focused explicitly on groundwater irrigation to determine land suitability by combining biophysical and socio-economic parameters (Worqlul et al., 2017). The study compared the estimated land suitable for irrigation with the estimated groundwater availability and the irrigation requirement at a 1 km resolution scale. Parameters for determining the land suitability for irrigation included topography, soil characteristics, rainfall deficit, crop water requirement, land use, population density, and road proximity. Groundwater availability was mainly derived from groundwater depth and the borehole yield map of the British Geological Survey (MacDonald et al., 2012). Results indicated that, on average, groundwater could irrigate about 8% of the land suitable for irrigation, with groundwater availability being the limiting factor.

The present study proposes to map and quantify those areas in continental Africa where groundwater irrigation potential exists and where there are both significant crop irrigation demands and optimal conduciveness for groundwater irrigation development from socio-economic and environmental perspectives. The study is complementary to the quantitative mapping of sustainable groundwater irrigation resource potential (GIRP) by Altchenko and Villholth (2015) since it adds driving factors of groundwater irrigation development to the hydrological, quantitative groundwater irrigation resource potential to refine it at a higher resolution based on an integrated, multi-criteria analysis. In this paper, the driving factors of groundwater irrigation development are defined as biophysical and socio-economic conditions that either constraint or are conducive to groundwater irrigation development. The objective is to provide a fully distributed assessment of the sustainable groundwater irrigation development potential in Africa (excluding small islands such as Seychelles, Cape Verde, and Comoros) with the purpose of highlighting areas where future investors should prioritise local investigations of groundwater irrigation development feasibility (either private, governments or donors).

4.2.2 Methodology

The present study is based on simple composite mapping analysis techniques (Lowry et al., 1995; Montz and Evans, 2001), using GIS to refine GIRP through a combination of geographical factors driving groundwater irrigation development, referred to as the groundwater irrigation development driver (GIDD). The study aims to locate and quantify those areas where it would be worthwhile to develop sustainable groundwater irrigation, referred to as sustainable groundwater irrigation development potential (GIDP). GIDD locates and ranks into conduciveness classes at a grid scale of 0.005-degree (about 0.5 x 0.5 km cell) the areas in Africa where it could be possible to develop sustainable groundwater irrigation, while GIDP locates and quantifies at the same grid scale those areas in Africa where it is worthwhile to develop sustainable groundwater irrigation. The approach is similar to Worqlul et al. (2017); the two primary distinctions are that this study takes into consideration the sustainability of the groundwater resource and the suitability of the land for groundwater irrigation.

The method initially maps GIDD at a 0.005-degree resolution (0.5 x 0.5 km cell) with a combination of factors that would limit further groundwater irrigation if a physical resource potential was present: (i) it identifies the driving factors (e.g., access to surface water) that constrain or are conducive to further groundwater irrigation development, with each factor dependent upon one or more parameters (Step 1 of Figure 13); (ii) it builds continent-wide distributed maps of each parameter (Steps 2 to 5 of Figure 13); (iii) it builds continent-wide distributed maps of each factor by combining the parameter maps when necessary (Step 6 of Figure 13) and; (iv) it combines the maps of the individual driving factors of GIDD through a composite mapping analysis in GIS (Step 7 of Figure 13). Finally, the development potential of sustainable groundwater irrigation (GIDP) is mapped by re-distributing the GIRP inside the areas which are more conducive to sustainable groundwater irrigation development (Step 8 of Figure 13). Also, a sensitivity analysis is performed to highlight the areas where the results are determined to be particularly robust.

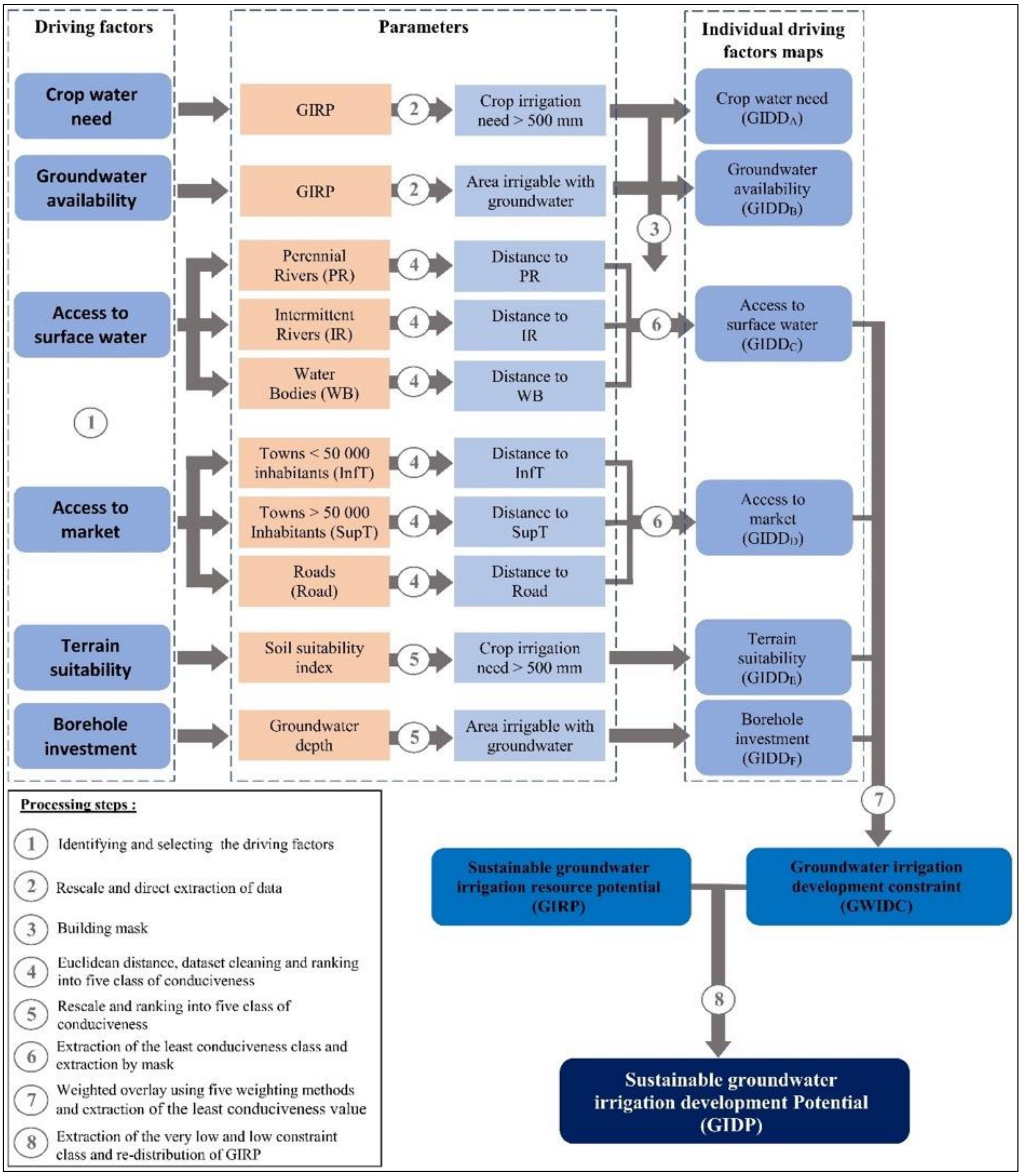


Figure 13: Diagram of the processing steps for mapping the composite Groundwater Irrigation Development Driver (GIDD) and the Sustainable Groundwater Irrigation Development Potential (GIDP).

4.2.2.1 Driving factors to further groundwater irrigation development: definition and data sources, and mapping

The driving factors for further GWI development are identified in recent literature. There are few specific quantitative or qualitative studies on GWI development (Forkuor et al. (2013); Villholth (2013); (Villholth et al. (2013a)), and most of the studies are dominated by surface water as the resource for irrigation. Table 3 summarises and describes, in no order, the driving factors for irrigation development in Africa.

Some factors could not be taken into consideration in the multi-criteria analysis approach because of the lack of adequate data at grid-cell and continental scale. The excluded factors include policies, institutions and services to the farmers, land tenure, return on investment, access to finance and farmer-led irrigation development. These factors will be discussed in section 4.3 which reviews the limits of the approach. One driving factor (access to groundwater) has been partly removed from the multi-criteria analysis: only groundwater depth is considered regarding the GWI investment. Additional aquifer characteristics will be discussed in 4.2. One driving factor (access to energy) has also been removed from the multi-criteria analysis to allow individual attention to be given to this factor in section 4.3. Also, one driving factor (elevation) is not applicable to GWI development since GWI is generally developed locally at proximity to the water resource, making elevation a negligible factor. Finally, the population driving factor has been integrated into the access to market factor.

The driving factors and the source of their datasets are described below and in Table 4:

A. **Groundwater availability**: this factor is linked to the physical availability of renewable water and the presence of rainfed cropping since further development of groundwater irrigation is unlikely when there are presently no cropping practices. The dataset used for this factor is directly extracted from the sustainable groundwater irrigation potential (GIRP) dataset provided by Altchenko and Villholth, (2015). GIRP is expressed as areas irrigable with groundwater, and the initial dataset has a 0.5-degree resolution (about 50 km x 50 km); this corresponds to areas in which 30% of the recharge is used for human needs, with irrigation considered only after satisfying all other human needs. Only those areas where there is potential for sustainable groundwater irrigation (GIRP) are considered; this means that groundwater irrigation development depends upon a threshold value of the factor, 0 in this case. The value of the dataset is later used for calculating GIDP also.

B. **Crop irrigation needs:** this factor is linked to the crop irrigation requirements. The dataset used for this factor was directly extracted from the intermediate datasets on crop water requirements developed by Altchenko and Villholth (2015) to calculate sustainable groundwater irrigation potential (GIRP). The irrigation water requirement is extracted for five crop groups (cereal, oil, root, pulse, and vegetable), then averaged. Sugarcane water irrigation requirements, which are available in the datasets, have been excluded from the average calculation because irrigation demand can be extremely high, and thus could artificially increase the average of crop irrigation requirements. Only the areas where crop water requirements are higher than 500 mm are considered.; this means that groundwater irrigation development depends upon a threshold value of the factor, 500 mm in this case. This threshold value is based on Wriedt et al. (2008) who developed a study in Europe regarding crop yield decreases resulting from several irrigation strategies ranging from no irrigation to full irrigation. On average for all crops, the results in Mediterranean areas indicated that crop yield decreased by only 16% if crop irrigation requirements were reduced by about 500 mm (from 1220 mm per year for the irrigation requirement for optimal growth to 724 mm per year for the irrigation requirement if there was a soil moisture deficit below 100 mm). Thus, if the crop water requirement is below 500 mm, there is no interest in investing in developing groundwater irrigation further.

C. **Access to surface water**: this factor refers to the distance to the closest available surface water resources and their availability throughout the year since groundwater becomes globally overlooked for irrigation when surface water is available throughout the year in adequate quantities. It is necessary to identify if the surface water is available from dams/reservoirs, perennial rivers, and seasonal rivers. Perennial rivers and dams/reservoirs can supply water for irrigation throughout the year while intermittent rivers are usually unavailable during the dry season when irrigation is most needed. Also, water from dams/reservoirs is often used in irrigation schemes located quite a distance from the reservoir itself. Thus, this factor is built on three parameters: the distance to intermittent rivers, the distance to perennial rivers, and the distance to dams/reservoirs.

The datasets used for the three parameters are from FAO (Geonetwork web portal) and consist of data about rivers and water bodies (i.e., lakes, dams, and reservoirs). The African river dataset derives from the World Wildlife Fund's (WWF) HydroSHEDS drainage direction layer and a stream network layer (Lehner et al., 2008), and it divides the rivers into two river regimes: perennial and intermittent. The river regime (perennial or intermittent) is estimated using a combination of the Strahler order and Aridity Index based on climatic average, and a comparison against available regime classifications, as shown in the Africa Water Resources Databases, the Times Atlas of the World, and the International Dialogue on Water and Climate (Pieser, interview). The regimes of the rivers from the Sinai area in Egypt are not specified in the database and were assigned to intermittent. Based on the river regime, the initial dataset was separated into two river datasets: perennial rivers and intermittent rivers. The African water bodies dataset is derived from NASA's Shuttle Radar Topography Mission (SRTM) Water Body Data (SWBD) (USGS, 2017) and does not include the rivers. Known soda/salty water bodies were deleted because their water quality is not suitable for irrigation. Waterbody extents are also excluded from the areas where groundwater irrigation can be developed.

D. **Access to market**: this factor is associated with three parameters; the distance to large towns, the distance to small towns, and the distance to the road network to reach those communities. The datasets used for the three parameters are from the Global Roads Open Access Data Set (gROADS) and The Global Rural-Urban Mapping Project (GRUMP) dataset (Balk et al., 2006) of NASA’s Socioeconomic Data and Applications Centre (SEDAC). These datasets encompass three further datasets: roads, town extents and settlement points. The GRUMP dataset for town extent points has been disaggregated into towns of less and more than 50,000 inhabitants to identify small towns from large towns. The settlement point dataset is used as additional information to the town extent, and each additional settlement point outside the town extent is converted into town extent by building a circle centred at the point. The radius of the circle is 1 km for towns with less than 50,000 inhabitants and 5 km for towns with more than 50,000 inhabitants. Town extents are excluded from the areas where groundwater irrigation can be developed.

E. **Terrain suitability for agriculture**: this factor is associated with the land appropriate for cropping when high inputs are applied since the farming systems using GWI are mostly market-oriented and are more likely to use inputs. The dataset used for this factor was directly extracted from the Global Agro-ecological Zones (GAEZ) V.3 dataset and, more precisely, the dataset corresponding to the terrain suitability index for agriculture with high inputs. The terrain suitability index for agriculture is based on the Harmonized World Soil Database (HWSD) (FAO/IIASA/ISRIC/ISS-CAS/JRC, 2012) and the slope derived by Verdin et al. (2007) from the Shuttle Radar Topography Mission (SRTM) at 90 m, following Sys et al. (1993) methodology. The parameters used to calculate the suitability index are nutrient retention capacity, rooting depth, drainage, salinity/sodicity, CACO3/CASO4, texture, and slope. The index of terrain suitability for agriculture is classified into seven suitability index classes ranging from very high suitability for agriculture to non-suitable. The initial dataset has a 0.083333-degree resolution (about 10 km x 10 km), and it has been bilinearly rescaled to a 0.005-degree resolution (about 0.5 x 0.5 km). In Ethiopia, the dataset is very similar to the land suitable for surface irrigation developed by Worqlul et al. (2017). It is also important to note that the HWSD for Africa is built using two sources (Digital Soil Map of the World and Harmonized continental SOTER-derived database) and the harmonization between the two databases has not been completed (FAO/IIASA/ISRIC/ISS-CAS/JRC, 2012). This situation is particularly noticeable at the border of Tunisia and the west border of both Egypt and Ethiopia where the soils do not match across the border.

F. **Borehole investment**: this factor is linked to the access to groundwater. Unlike hand-dug wells, deep water tables require significant investment to use groundwater as a source for irrigation, before considering the energy costs of running the lifting device. As a result, this factor directly links to the depth of the water table. The dataset used for this factor is extracted from the NERC – GWGW / BGS dataset which estimates groundwater depth. In the absence of much observed groundwater-level data over the continent, the depth to groundwater was estimated by testing several modeling techniques using continental-scale data for geology, geomorphology, and rainfall and by comparing these with observed data. However, best estimates were developed through an empirical approach using rainfall, geology, and a set of rules (Bonsor and MacDonald, 2011). The dataset is classified into six depths of groundwater (from 0 to 7 m, from 7 to 25 m, from 25 to 50 m, from 50 to 100 m, from 100 to 250 m, and over 250 m). The initial dataset has a 0.05-degree resolution (about 5 km x 5 km) and has been bilinearly rescaled to a 0.005-degree resolution (about 0.5 x 0.5 km). Madagascar is missing from the dataset due to a lack of information. It is estimated that the groundwater level in that country is primarily less than 25 m deep (MINEAU, 2010.), so the depth of groundwater in Madagascar was assigned to the 7 to 25 m class.

Table 3: Driving factors of irrigation development in Africa identified from recent literature without considering water resource availability and the crop water requirement (in no particular order).

Driving factor	Description	References
Water availability	Further sustainable irrigation development should occur only in areas where there is physical availability of renewable water and where there are presently cropping practices.	FAO (1997); FAO (2005); You et al. (2011); Xie et al. (2014); Neumann et (2011); Droogers et al. (2012); Worqlul et al. (2017)
Crop water need	Irrigation development should occur only in areas where it significantly increases crop yield as compared to rainfed crops and where it limits the impacts of unfavourable climatic conditions (i.e., drought) on crop production.	
Terrain suitability	Slope inferior to 2% and soils with specific characteristics (well-drained soil, silty clay loamy texture, soil depth > 100 cm, surface stoniness to 0%, subsurface stoniness < 40%, calcium carbonate < 30%, gypsum < 10%, salinity < 8 mmhos/mm and alkalinity < 15 ESP) are usually more relevant for irrigation development. However, drip irrigation allows slope to 20%, and hill-side irrigation can be found in mountainous areas in Africa (Droogers et al., 2012). Soil fertility and characteristics can be upgraded with inputs or agricultural techniques.	
Elevation	Irrigation development is limited when the elevation of the irrigated crop is much higher than the elevation of the water source.	You et al. (2011); Xie et al. (2014); Droogers et al. (2012)
Access to market	Areas at proximity to town and road networks are more relevant for irrigation development. Access to market for selling the crops but also for purchasing inputs (i.e., seeds, fertilisers, pesticides), energy (i.e., diesel) or irrigation technologies, including maintenance pieces and drilling hardware, plays an important role.	Neumann et (2011) ; Droogers et al (2012) ; Villholth (2013) ; Worqlul et al (2017) ; (Villholth et al (2013b)
Distance to surface water	For irrigation with surface water, the distance to the main water source influences irrigation development: if it is too far, investment cost is too high. In the case of GWI, this factor is considered to account for the increasing interest of groundwater if surface water is distant or not available.	Droogers et al (2012) ; Xie et al (2014)
Population	Areas with too many (e.g., cities) or too few inhabitants (e.g., no labour available) are less relevant for irrigation development.	Xie et al (2014) ; Droogers et al (2012) ; Worqlul et al (2017)
Return of Investment	Irrigation is relevant when there is a positive difference between the crop production sold at market price and the crop production cost (i.e., investment, operating, inputs and labour).	You et al. (2011); Xie et al. (2014)

Driving factor	**Description**	**References**
Policy, institution, and services to the farmer	Irrigation development, especially GWI, can be promoted by national policies and institutions. Political stability, corruption, and level of democracy or autocracy, as well as services which inform and support farmers in modern farming choices (i.e., irrigation technologies and seed) can play an important role also.	Neumann et al. (2011); Villholth (2013); Villholth et al. (2013b)
Land tenure	Irrigation development (and the investment linked to it) is less favourable when there is insecure land tenure.	Villholth (2013)
Access to finance	Irrigation development (investment and initial running costs) is constrained when there is difficult access to loans from private money lenders or formal credit institutions or access to benefits from subsidies or donors	Villholth (2013); (Villholth et al. (2013b)
Access to energy	Cheap access to energy for running the pump is favourable for irrigation development. Energy from electricity has lower running costs than fossil fuel, but rural electrification in Africa is low. Fuel subsidies and alternative energy sources (i.e., biofuel, solar) are still limited in Africa.	
Access to groundwater	The aquifer characteristics (e.g., borehole yield, water depth, and aquifer storage) can limit GWI if groundwater is not an accessible and reliable resource	Forkuor et al (2013) ; Villholth (2013) ; (Villholth et al (2013b)
Farmer-led irrigation development	Farmers assume a driving role in improving their water use for agriculture and developing small private irrigation, influencing in the process the whole irrigation chain from neighbouring farmer to policymaker and development agencies.	De Friture and Giordano (2014); Woodhouse et al. (2017)

Table 4: Data sources of the selected driving factors.

Driving factors	Parameters	Initial dataset source	Resolution when applicable (degree)
A. Groundwater availability	Area irrigable with renewable groundwater	Altchenko and Villholth (2015) (http://waterdata.iwmi.org/pages/data_search.php?search_term=groundwater)	0.5°
B. Crop water need	Crop water need		
C. Access to surface water	Distance to perennial river	African river (http://www.fao.org/geonetwork/srv/en/metadata.show?id=37333	
	Distance to intermittent river		
	Distance to water bodies	Radar Topography Mission (SRTM - WBD) Water Body Data (http://www.fao.org/geonetwork/srv/fr/metadata.show?id=30924	
D. Access to market	Distance to small town extent (< 50000 inhabitants)	Global Rural-Urban Mapping Project (GRUMP) dataset (Balk et al., 2006 Urban extents ((http://dx.doi.org/10.7927/H4GH9FVG)) Settlement point ((http://dx.doi.org/10.7927/H4M906KR)	0.08333333°
	Distance to large town extent (> 50000 inhabitants)		
	Distance to road network	gROADS (http://dx.doi.org/10.7927/H4VD6WCT	
E. Terrain suitability for agriculture	Soil suitability index for agriculture with high inputs	Global Agro-ecological Zones (GAEZ) V.3 (http://gaez.fao.org/Main.html#)	0.08333333°
F. Borehole investment	Depth to water table	NERC – GWGW / BGS (http://www.bgs.ac.uk/research/groundwater/international/africangroundwater/requestMap.cfm)	0.05°

4.2.2.2 Construction of the individual groundwater irrigation development driver maps

Each driving factor depends upon one or more parameters. The analysis builds a continent-wide distributed map of each parameter at a 0.005-degree resolution (0.5 x 0.5 km cell), bins the value (e.g., distance to perennial river) into classes that indicate the level of conduciveness of groundwater irrigation development, maps the individual GIDD maps, and then combines the individual maps into GIDD.

For the driving factors of groundwater availability (A) and crop water need (B), the initial dataset is rescaled at a 0.005-degree resolution and cells with a value superior to 0 for groundwater availability (A) and superior to 500 mm per year for crop water need (B) are extracted to create the individual GIDD maps (Step 2 of Figure 13, Table 5). Only cells combining both threshold values will be considered for the remainder of the analysis; this means that their individual GIDD maps are used as masks when the other individual GIDD maps are built (Step 3 of Figure 13).

For the driving factors of access to surface water (C) and access to market (D), parameter maps show the distance to the closest feature (intermittent rivers, perennial rivers, water bodies, small towns, large towns or roads). The process is based on a country assessment to take into consideration that there are no international exchanges or transfers between nations (i.e., no international water transfers or food trade). Then, the distances are binned into five classes of the level of conduciveness to GWI development (1=extremely conducive, 2=highly conducive, 3=moderately c conducive, 4=slightly conducive and 5= non-conducive), ranked from the most favourable class for groundwater irrigation development to the least favourable (Step 4 of Figure 13). The ranking details are provided in Table 5 and are derived from literature (Droogers et al., 2012; Wale et al., 2013; Worqlul et al., 2017), experience, and common sense. The ranking of access to surface water (A) reflects two considerations; since the surface water is easier to use than groundwater, it is assumed that proximity to surface water limits the use of groundwater for irrigation. As a result, the conduciveness exerted by the distance to surface water on groundwater irrigation development constraints (GIDD) is less significant when this distance is small and even more so if the surface water is perennial. However, it is assumed that there is extreme conduciveness near intermittent rivers since boreholes are often located in the associated alluvial groundwater zone. The ranking of conduciveness exerted by the access to market (B) reflects that the conduciveness is higher closer to a city or road. Finally, the analysis combines the parameters into individual driving factor maps by extracting the lowest level of conduciveness of each cell to be conservative with the approach (Step 6 of Figure 13). For example, as it relates to access to surface water, this means that if the class of conduciveness is 5 (not conducive) because the area is in the vicinity of a lake, the extracted class of conduciveness is 5 even if the classes of conduciveness of the other parameters are lower.

For the driving factors of terrain suitability for agriculture (E) and borehole investment (F), the initial dataset is already arranged into classes. The process rescales the dataset and bins the existing classes into the five classes of conduciveness (Step 5 of Figure 13, Table 5). The conduciveness exerted by the index of soil suitability for agriculture (C) stems from the aggregation of existing classes of the soil suitability index. The conduciveness exerted by borehole investment (D) mirrors the increase in cost associated with the depth of the borehole.

Table 5: Ranking of the parameters into classes of constraints

Driving Factors	Parameters	Class of conduciveness					Exclusion (No Data)
		Extremely conducive (1)	Highly conducive (2)	Moderately conducive (3)	Slightly conducive (4)	Non-conducive (5)	
A. Groundwater availability	Area irrigable with renewable groundwater	-	-	-	-	-	0
B. Crop water need	High crop water need (mm)	-	-	-	-	-	< 500
C. Access to surface water	Distance to perennial river (km)	> 10	5 – 10	3 – 5	1 – 3	< 1	–
	Distance to intermittent rivers (km)	< 1 and > 10	5 – 10	1 – 5	–	–	–
	Distance to water bodies (km)	> 15	10 – 15	5 – 10	2 – 5	< 2	0
D. Access to market	Distance to small town extent (km)	< 10	10 – 20	20 – 30	30 – 50	> 50	0
	Distance to large town extent (km)	< 20	20 – 40	40 – 60	60 – 100	> 100	0
	Distance to road network (km)	< 5	5 – 10	10 – 15	15 – 20	> 20	–
E. Terrain suitability for agriculture	Soil suitability index	Very high and high	Good	Median and Moderate	Marginal	Very Marginal	Not suitable and water
F. Borehole investment	Groundwater depth (m)	< 7	7 – 25	25 – 50	50 – 100	> 100	> 100

4.2.2.3 Construction of the sustainable groundwater irrigation development driver map and the sustainable groundwater irrigation development potential map

The analysis combines the maps of the individual driving factors (access to surface water, access to market, terrain suitability and borehole investment) into the GIDD map through a composite mapping analysis in GIS first, using different weighting methods to determine the irrigation development obstacles per cell and second, extracting per cell the lowest level of conduciveness from the results of the various weighting methods to avoid overestimating the areas favourable to GWI development (Step 7 of Figure 13, annex 2). Figure 14 shows the different sets of weights applied to the individual GIDDs, which are the equal-weight method for each factor and four alternative weight sets, as proposed by Malczewski (1999) for use in GIS multi-criteria analysis. The equal-weight method (W1) assumes that all the factors have the same influence, while the other methods rank the relative influence of the various factors. The ranking sum (W2) and ranking reciprocal (W3) rank the factors while the pairwise comparison method (W4) and rating method (W5) rank the factors against each other and apply a rating, respectively. Hierarchizing and rating have been performed with common sense and expertise. Later, cells, where no groundwater irrigation is possible, are removed from the GIDD; this corresponds to the areas where inside water bodies, town extensions and terrain are not suitable for agriculture. The resulting values are reclassified into GIDD classes for display purposes as shown in Table 6.

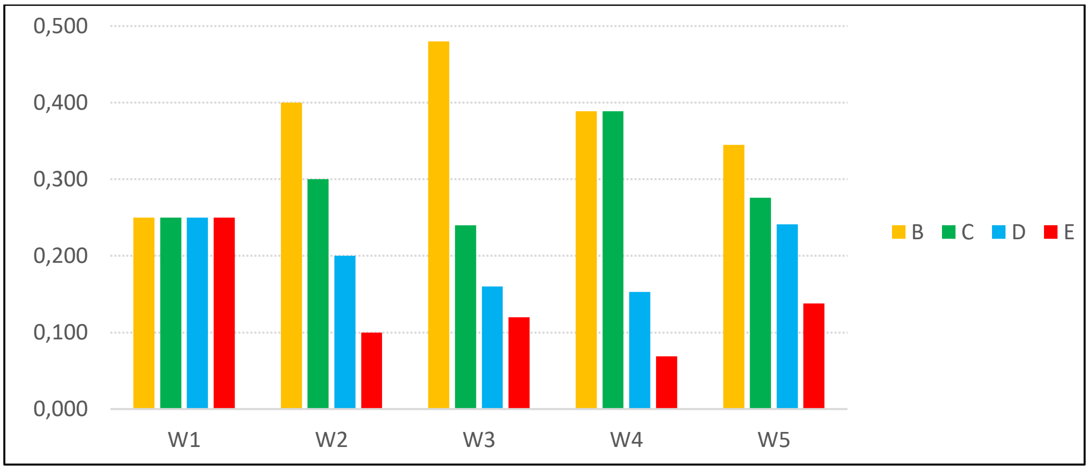


Figure 14: Weights for the different distributed factors A to E according to the different weighting sets: equal-weight method (W1), raking sum method (W2), ranking reciprocal method (W3), pairwise comparison (W4) and the rating method (W5).

Table 6: Ranking of the distributed groundwater irrigation development constraint (GIDD) into classes of constraint.

Value	GIDD class description
1 – 1. 7	Extremely conducive
1.7 – 2.6	Highly conducive
2.6 – 3.4	Moderately conducive
3.4 – 4.2	Slightly conducive
4.2 – 5	Non-conducive

Finally, the development potential of sustainable groundwater irrigation (GIDP) is mapped by re-distributing the GIRP inside the areas which are the more conducive to sustainable groundwater irrigation development (Step 8 of Figure 13). Because of the resolution difference between GIRP (0.5-degree resolution) and GIDP (0.005-degree resolution), sustainable groundwater irrigation development potential (GIDP) is first built by extracting those cells with significant conduciveness to sustainable groundwater irrigation development (i.e., extremely and highly conductive area), then by homogeneously distributing the GIRP into the extracted cells according to the following process. The areas and the number of cells for extremely and highly conducive GIDD are calculated inside each cell of the GIRP. If the calculated area is superior to the area for GIRP, then GIDP corresponds to GIRP divided by the number of cells. This process means that the quantitative groundwater irrigation potential is homogeneously distributed into those areas where groundwater irrigation development potential is the most conducive and worthwhile to be fully developed. If the calculated area is inferior to the GIRP area, then GIDP corresponds to that area. This outcome means that the quantitative groundwater irrigation potential cannot be fully developed because there is insufficient conduciveness for groundwater irrigation development.

4.2.3 Results

4.2.3.1 Sustainable groundwater irrigation development drivers (GIDD) map

GIDD locates and ranks into conduciveness classes of irrigation development at a grid scale of 0.005-degree (about 0.5 x 0.5 km cell) those areas where it is worthwhile to develop sustainable groundwater irrigation. This is determined by combining through five weighting methods the individual GIDDs, then by extracting the lowest class of conduciveness. The individual GIDD maps and the maps resulting from the different weighting methods are presented in annex 2. Figure 15 displays the GIDD over the continent and Table 7 presents the statistical summary of the four driving factors used for the weighting method. Without considering the groundwater availability (A) and the crop water need (B), the main factor influencing groundwater irrigation development is access to surface water (mean: 3.22) while borehole investment (mean 2.17), and terrain suitability for agriculture (mean: 1.93) are of less significance, and access to market (mean: 1.66) is the least significant driving factor. The influence of the partial GIDDs needs to be linked to the weighting method sensitivity analysis developed in section 3.1.

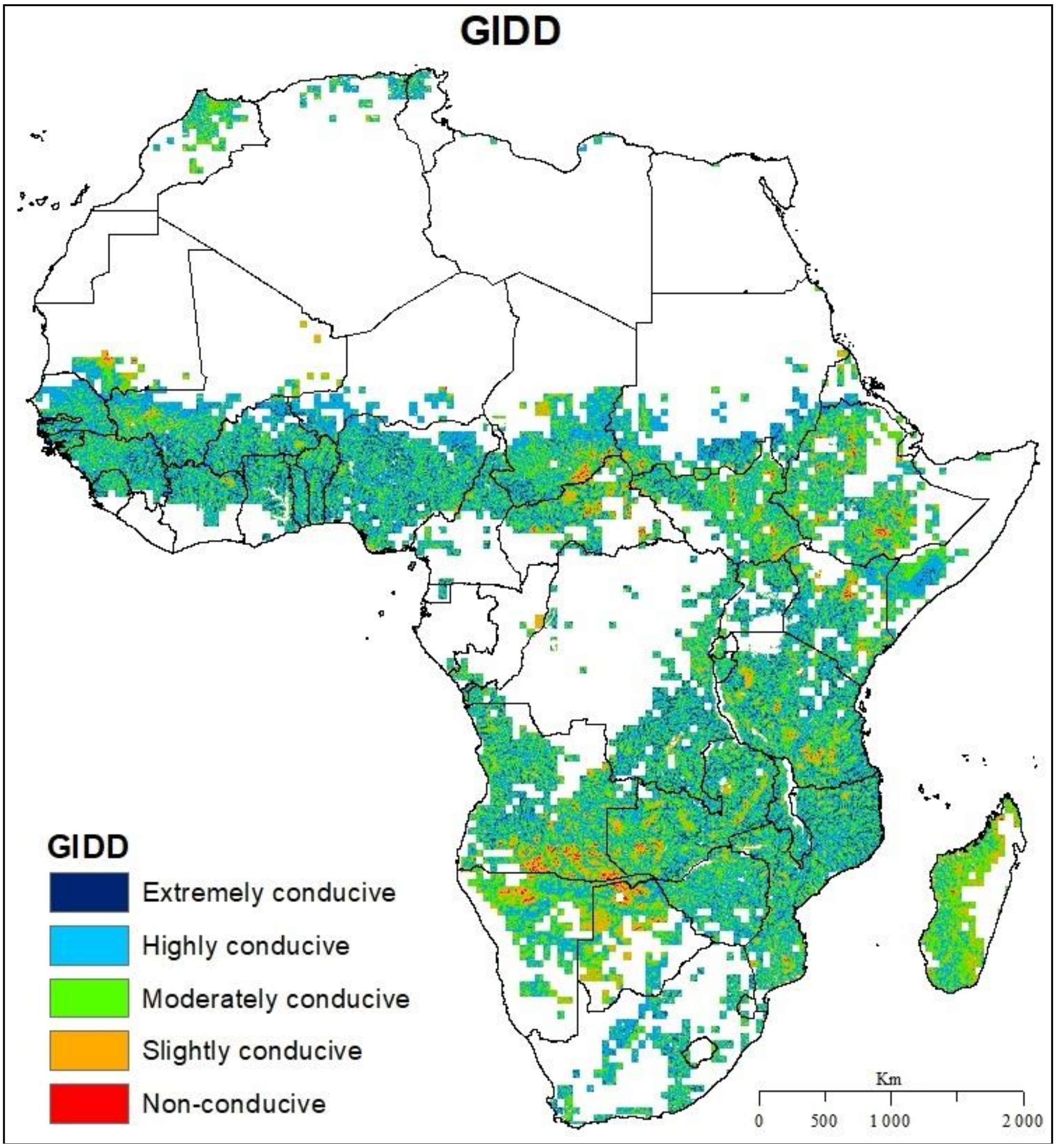


Figure 15: Sustainable groundwater irrigation development driver (GIDD) map ranked into five class of conduciveness.

Table 7: Statistical summary of the different driving factors of the groundwater irrigation development

Driving Factor	min	max	mean	Standard deviation	coefficient of variance (%)
C	1	5	3.22	1.14	35.4%
D	1	5	1.66	1.08	65.1%
E	1	5	1.93	1.06	54.9%
F	1	5	2.17	1.16	53.5%

Results show that GIDD is located along two visible corridors: a west-east stripe going from Senegal and Guinea to Ethiopia and a sizable north-south stripe along the Eastern part of Africa from Ethiopia to Angola and Zimbabwe. Arid and semi-arid areas (i.e., Sahara and Namib deserts, Kalahari and Eastern part of the Horn of Africa) and equatorial areas (i.e., South-western part of the West Africa coast and most of Gabon, Republic of Congo and Democratic Republic of the Congo) are quasi-excluded (no colour) from sustainable groundwater irrigation development because there is no groundwater available for irrigation or because the crop water need from irrigation is not sufficient to be worthwhile investing in irrigation, respectively.

Globally, results show no extreme for the conduciveness class with most of the cells ranging from highly (light blue) to slightly (orange) conductive. In the perennial river zones, the proximity of the river generally is moderately conducive (green) to sustainable groundwater irrigation development, while highly (light blue) and extreme (dark blue) conduciveness is found between rivers. In the intermittent river zones, GIDD surrounding the rivers is moderately (green) to extremely (dark blue) conducive, but the level of conduciveness class decreases to moderately (green) and slightly (orange) conducive in areas with both a low population density and a weak road network while within the vicinity of reservoirs.

Areas non-conducive (red) to sustainable groundwater irrigation development are primarily found in pockets where there is little population, a weak road network, and deeper groundwater. This corresponds to areas at the border of Chad and CAR, the Ethiopian highlands and the area at the border of Angola, Botswana and Namibia which includes some natural reserves like the Etosha or the Okavango Delta.

There is a visible highly conducive (light blue) area along the south of the Sahara Desert which corresponds to the Sahel where there are intermittent rivers and a relatively shallow aquifer. Pockets on highly (light blue) to extremely (dark blue) conducive development are also found in the South of Somalia and in South Africa which corresponds to intermittent rivers zones with good density of population and suitable terrain for agriculture.

The sensitivity analysis should assist in better understanding the subtleties of the factors and the method's uncertainty.

4.2.3.2 Sustainable groundwater irrigation development potential (GIDP) map

GIDP locates and quantifies at a grid scale of 0.005-degree (about 0.5 x 0.5 km cell) those rainfed areas in Africa that are worthwhile to develop with renewable groundwater irrigation. It is mapped by re-distributing the GIRP from Altchenko and Villholth (2015), inside the areas which are the more conducive to sustainable groundwater irrigation development. Figure 16 illustrates the continent-wide distribution of GIDP, expressed as areas that are worthwhile developing with sustainable groundwater irrigation. It also compares the results to the areas equipped for irrigation in Africa in 2005 (Siebert et al., 2013) and shows development potential on a per-country basis, expressed as a percentage of the GIRP, highlighting those nations whose current irrigation is already exceeding GIDP.

As previously stated, regarding GIRP, sustainable groundwater irrigation development potential (GIDP) occurs mostly outside the desert areas in two important corridors: the Sahel region and south of it, and Eastern-Southern Africa where more than 90% of the groundwater irrigation potential (GIDP) is worth developing. This means that groundwater irrigation development is mainly limited by the resource itself rather than by biophysical and socio-economic factors which are conducive to its development. Total development potential (GIDP) across the continent is 19.3 x 10^6 ha, while total groundwater irrigation potential (GIRP) across the continent is 44,8 x 10^6 ha. Table 8 provides country-specific information on the distribution of the GIDP in Africa compared to the GIRP and the areas equipped for irrigation (Siebert et al., 2013). Approximately 57% of groundwater irrigation resource potential (GIRP) does not appear in areas with potential for sustainable groundwater irrigation development due to driving factors that constraint the development. These missing GIDP zones are primarily located in Central Africa (CAR, DRC, Gabon, Rep. of Congo), south of Eastern Africa, and Liberia where there is physical groundwater irrigation potential (GIRP) but crop irrigation demand is inferior at 500 mm per year (Figure 16). When compared to the dataset from Siebert et al. (2013), who estimated the area equipped with groundwater irrigation in 2005 to be 2.4 x 10^6 ha, it appears that groundwater irrigation can still be developed, except in the Maghreb region and South Africa where GIDP is already exhausted (Figure 16). When considering countries where the sustainable groundwater irrigation development potential is not already exhausted, the areas irrigable with sustainable groundwater are 75 times more important than the current areas equipped with groundwater irrigation. The map shows untapped groundwater irrigation development potential in the semi-arid Sahel, the Eastern Africa region and Southern Africa but the development is limited to an area less than 0.2 ha per cell of twenty-five hectares. Better development potential exists along a west-east line from Angola to the North of Mozambique and along a west-east line south of the Sahel from Guinea to CAR where the potential development is mainly between 0.5 to 2 ha per cell, but there are also some pockets with development potential higher than 2 ha per cell (e.g., Ivory coast, extreme south of Mali, Tanzania, Zambia). The West of Ethiopia also presents good potential for development at close to 5 ha per cell.

GIDP results indicate that sustainable groundwater irrigation development could essentially occur in areas inferior to two hectares per cell of twenty-five hectares; this indicates that sustainable groundwater irrigation development should focus on smallholders and in particular very smallholders in the semi-arid Sahel and Eastern Africa region where the development of groundwater irrigation could level up livelihoods by providing food production from reliable and affordable water resources.

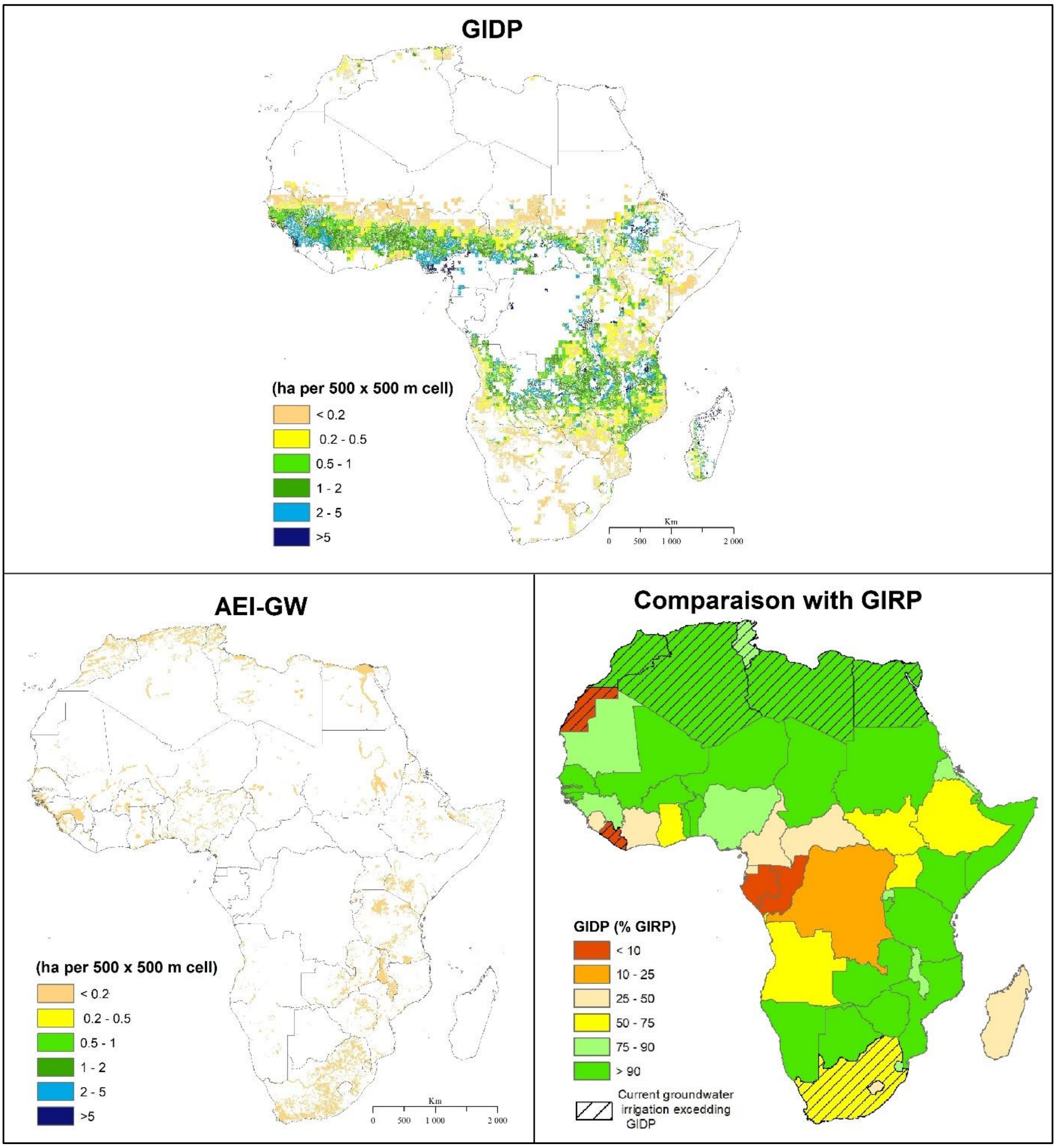


Figure 16: Sustainable groundwater irrigation development potential (GIDP) and area equipped for irrigation with groundwater (AEI_GW) in 2005 provided by Siebert et al. (2013), both expressed in hectare per cell at a resolution of 0.005° (cell area about 25 ha), and compared to the sustainable groundwater irrigation resource potential (GIRP) estimated by Altchenko and Villholth (2015).

Table 8: Gross sustainable groundwater irrigation development potential and cultivated area per country in Africa

Country	**Area of GIDP** (10^3 ha)	(% GIRP)	To develop (10^3 ha)	**Area of cropland irrigable with groundwater (GIRP)** (10^3 ha) [a*]	**Area equipped for irrigation irrigated with groundwater** (10^3 ha) [b*]
Algeria	48	100%	0	48	361,3
Angola	1671	58%	1655	2903	15,8
Benin	235	100%	233	235	2,2
Botswana	23	92%	22	25	0,8
Burkina Faso	136	100%	133	136	3,0
Burundi	73	100%	73	73	0,0
Cameroon	824	28%	824	2990	0,2
Central African Republic	933	31%	933	2978	0,0
Chad	249	99%	243	251	6,0
Côte d'Ivoire	410	34%	410	1219	0,0
Democratic Republic of Congo	1827	19%	1827	9751	0,0
Djibouti	3	100%	2	3	0,7
Egypt	1	100%	0	1	309,2
Equatorial Guinea	75	28%	75	271	0,0
Eritrea	6	86%	2	7	3,6
Ethiopia	1301	73%	1298	1773	2,8
Gabon	54	2%	54	2519	0,0
Gambia	13	100%	13	13	0,0
Ghana	367	62%	355	595	11,8
Guinea	1076	87%	1076	1230	0,5
Guinea-Bissau	91	100%	87	91	3,9
Kenya	204	96%	203	213	1,1
Lesotho	3	43%	3	7	0,1
Liberia	0	0%	0	956	0,0
Libya	11	100%	0	11	444,1
Madagascar	1007	35%	1007	2868	0,0
Malawi	245	90%	245	273	0,1
Mali	383	99%	382	386	1,0
Mauritania	21	95%	16	22	5,3
Morocco	51	100%	0	51	642,7
Mozambique	893	100%	892	896	1,0
Namibia	38	97%	37	39	1,5
Niger	7	100%	6	7	1,4
Nigeria	2129	79%	2063	2683	66,5
Republic of Congo	141	4%	141	3213	0,0
Rwanda	49	89%	49	55	0,1
Senegal	179	100%	170	179	9,4
Sierra Leone	304	47%	304	652	0,0
Somalia	20	100%	10	20	10,1
South Africa	68	67%	0	101	126,2
South Sudan	698	52%	698	1338	0,4
Sudan	203	100%	134	203	68,7
Swaziland	8	89%	7	9	1,0
Tanzania	1245	97%	1228	1281	16,6
Togo	126	99%	126	127	0,0
Tunisia	9	90%	0	10	255,7
Uganda	152	62%	152	246	0,1
Western Sahara	0	0%	0	0	0,0
Zambia	1584	95%	1578	1672	6,5
Zimbabwe	140	99%	120	141	19,7
Total	19,3 10^3	43%	18.9 10^3	44.8 10^3	2,4 10^3

*Values can slightly differ compared to the published article by Altchenko and Villholth (2015) because of the different geoprocessing tool use in their paper and this paper

(a) Altchenko and Villholth (2015) (b) Siebert et al. (2013)

4.2.4 Discussion

4.2.4.1 Sensitivity analysis for GIDD

The results are discussed through three sensitivity analysis tests that highlight the relevance of using all the driving factors, and the uncertainty generated by the methodology. Full details of the methodology and results can be found in annex 3.

The first test, called map removal sensitivity analysis (Lodwick et al., 1990), identifies whether one factor is dominating the results or if one factor could be removed from the calculation without significantly affecting the results. The test calculates the Sensitivity Index (SI), expressed as the percentage of the variation between GIDD and GIDD when one factor is removed (annex 3). SI for each driving factor and the five weighting methods shows no extreme importance of any of the factors and enough variation to justify considering the four driving factors in the calculation of the GIDD. Access to market (D) has the highest variation and borehole investment (F) seems to be the least sensitive factor.

The second test is performed to determine the level of uncertainty regarding the driving factor of crop water need (B) and from the aggregation of levels of conduciveness of the groundwater irrigation development driver. It calculates GIDP with different threshold values (annex 3). The primary conducive factor is the crop water need (B) because the threshold value affects the equatorial zone which has a high GIRP. Concerning the level of conduciveness, the main increase in areas where it is worthwhile to develop groundwater irrigation further occurs when highly conducive areas are cumulated to extremely conducive areas (the addition of the other conduciveness classes is not significant). Not surprisingly, the availability of sustainable groundwater (A) limits more the areas where irrigation can be developed than other driving factors, except the crop water need (B).

The third and final test provides an understanding of the uncertainty generated by the driving factors of access to surface water (C) and access to market (D), which depend on the rankings into five classes of conduciveness of three parameters. No test was performed on the driving factors of terrain suitability for agriculture (E) and borehole investment (F) because the original data are already provided in classes. Two additional rankings are performed for each parameter (C and D), and sustainable groundwater irrigation development potential (GIDP) is then calculated with the twenty-seven combinations possible for each of the driving factors (annex 3). Most of the uncertainty on access to surface water (A) is in the perennial river zones where there is lower conduciveness to groundwater irrigation development. Also, GIDP appears to be close to the maximum of the GIDP calculated from the twenty-seven combinations, indicating that GIDP might have been overestimated by this approach. In contrast, there is little uncertainty from access to market (D) mainly occurring along two west-east lines: from Angola to south of Tanzania and from Gambia to west of Ethiopia, inside the perennial river zone.

Figure 17 summarises the level of uncertainty of GIDP per country and, as previously stated, demonstrates that countries in drier areas have the lowest uncertainty related to GIDP (e.g., Senegal, Sudan or Mozambique) while countries under equatorial conditions have the highest uncertainty regarding the results (e.g., DRC or Cameroon) because of the driving factor of crop water need (B).

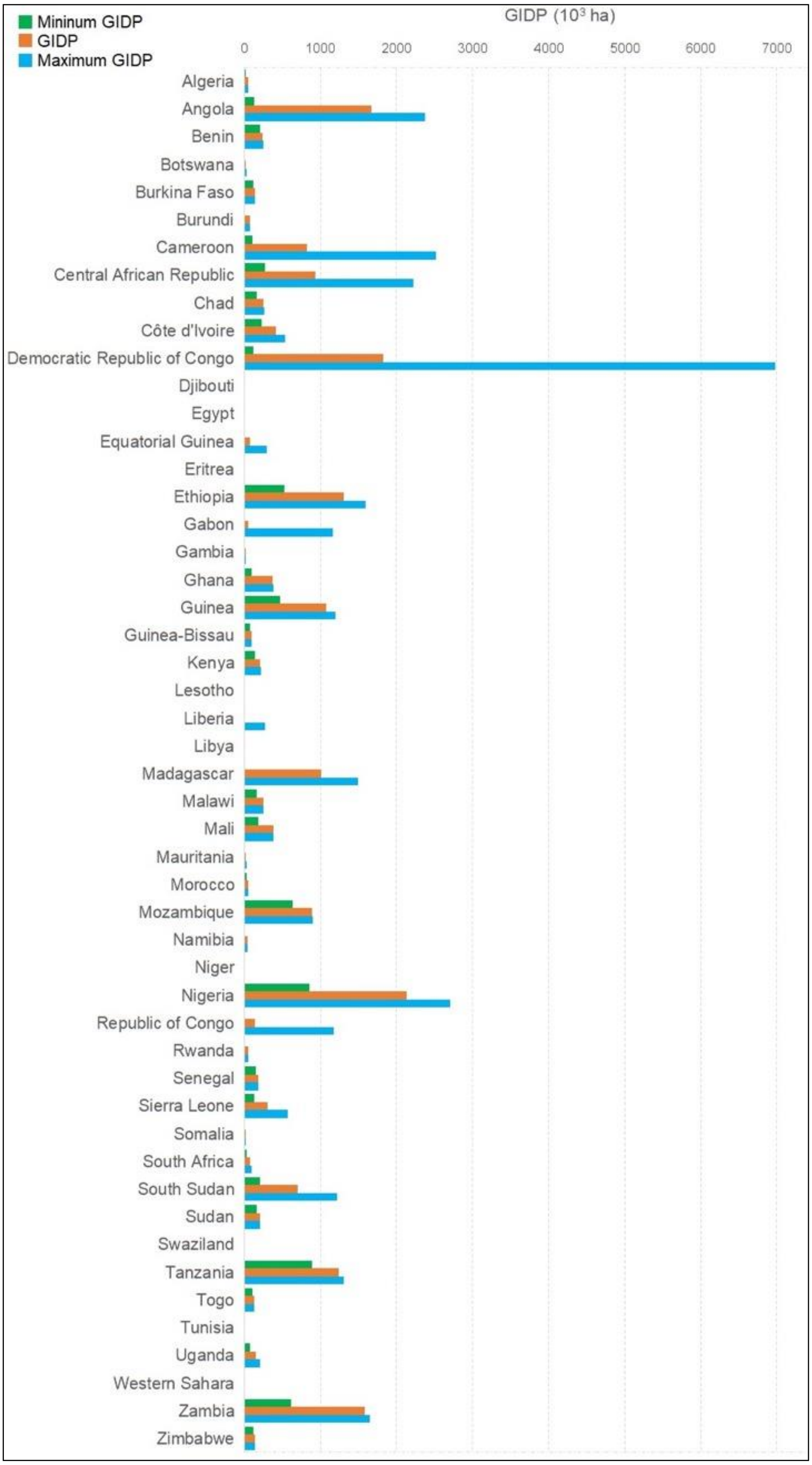


Figure 17: Level of uncertainty of sustainable groundwater irrigation development potential (GIDP) per country.

4.2.4.2 Aquifer characteristics

Borehole yield and groundwater quantity also have a significant impact on groundwater's use for irrigation purposes. First, fractured aquifers in basement rocks, which cover about 34% of Africa, have little primary permeability or porosity (MacDonald et al., 2013). This condition limits groundwater storage and borehole yield, which can be lower than 1 L.s^{-1}, and thus the use of groundwater for irrigation. Based on pumping 8 hours per day during a 240-day cropping period, (e.g., a yield of 1 L.s^{-1} brings 3 mm of water per day to 1 ha), Figure 18 presents the number of boreholes per cell (25 ha) which are necessary to provide adequate groundwater quantity to irrigate the GIDP area, according to borehole yield map from MacDonald et al. (2013). The number of boreholes per cell is only one for 58% of the cells, less than 6 for 84% of the cells, and more than 20 for 3.5% of the cells. The latter case is particularly significant in Benin, Nigeria, and Cameroon where basement rock covers most of the countries (yield inferior to 0.5 L.s^{-1}). However, the low yield can still be adequate for rural demand and smallholder farming. Collector wells[25] have been designed to maximize the yield from the basement weathered zones (MacDonald and Davies, 2000). Groundwater storage has been also assessed using data from MacDonald et al. (2013). Groundwater storage doesn't limit GIDP when groundwater storage is higher than 1 10^{6} m km^{-2} (map not shown). Unfortunately, the dataset doesn't provide details when the groundwater storage is less than this value. In the areas where groundwater storage is less than 1 10^{6} m km^{-2}, tests on groundwater storage show that limitation of GIDP by the groundwater storage is insignificant: less than 1% of the cells are affected if groundwater storage is under 0.2 10^{6} m km^{-2}. Second, groundwater quantity is directly linked to the groundwater recharge when the sustainability of the resource is considered. Groundwater recharge is correlated not only to precipitation quantity but also to precipitation intensity. In the context of climate change, lower precipitation and soil moisture is expected in both Northern and Southern Africa in the 21st Century (Gan et al., 2016) while increases in extreme rainfall could occur in the Sahel during May and July and in Eastern Africa with extreme wet days (Naing et al., 2014). These changes in precipitation variability and

---

[25] A collector well consists of a large diameter central shaft with horizontal radials penetrating the surrounding aquifer. These radials are positioned to penetrate the high permeability zone at the base of the weathered profile. The resulting well has a large storage, but also a high seepage rate and therefore provides a higher sustainable yield (Macdonald et al., 1995)

intensity might affect groundwater recharge positively or negatively, reducing the groundwater available for irrigation in the latter case.

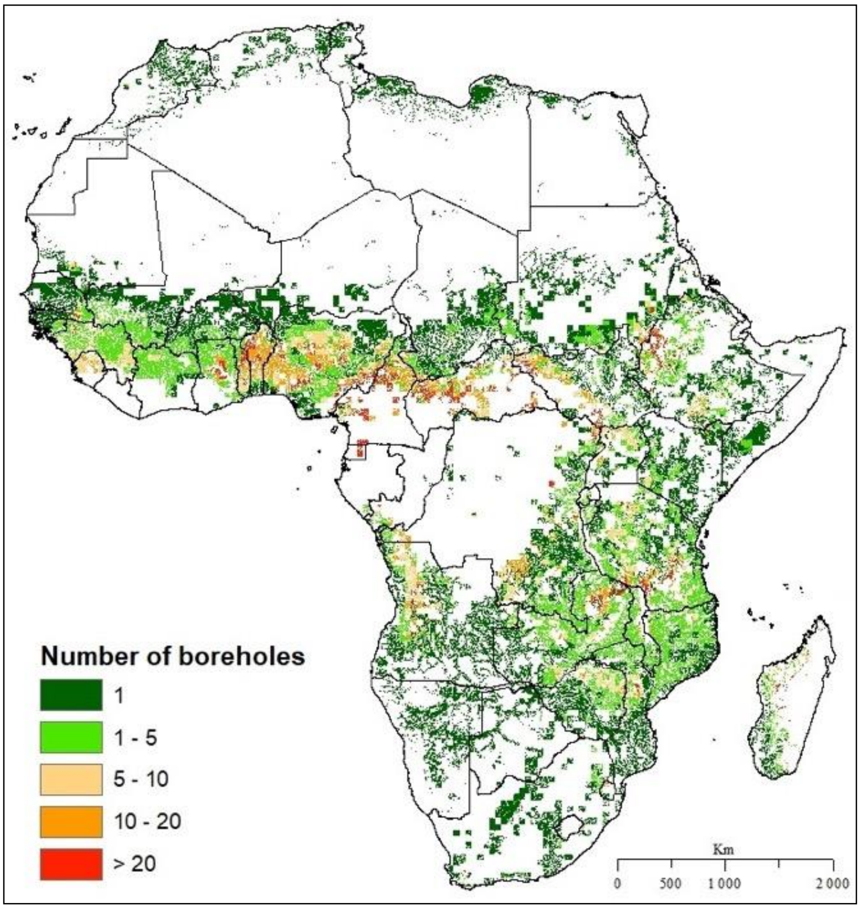


Figure 18: Number of boreholes per cell necessary to irrigate the GIDP areas, based on borehole yield map from McDonald et al. (2013) and 8 hours per day of pumping during a 240-day per year cropping season.

4.2.4.3 Energy for lifting devices

Energy costs and access to energy have been identified as driving factors to further GWI development (Villholth, 2013) because the cost of pumping or lifting water is closely related to the amount of energy used. There are several energy sources for running lifting devices such as humans (i.e., hand pump), electricity, diesel, or renewable energy. Treadle pumps, commonly used in Africa, have no running cost and low maintenance requirements but they are not generally suitable for deep groundwater and require many labour hours (IFPRI, 2012). Running costs for diesel and petrol-powered pumps are higher than using electricity, so low rural electrification in SSA tends to limit groundwater irrigation. Within the broad spectrum of solutions, solar-powered irrigation has gained prominence (IRENA, 2016) and particular attention is currently placed on solar irrigation systems in SAA (Wazeda et al., 2018). Such systems utilize solar photovoltaic and solar thermal technologies, the latest being more suitable for smallholders and small-scale operations. Africa offers significant potential for renewable energy such as solar energy, wind energy, and bioenergy, the first two being zero-cost energy if the initial investment is not considered. In particular, Eastern Africa and Southern Africa have significant solar energy potential (Hermann et al., 2014). Considering the GIDP results, it appears that solar powered lifting devices and their decreasing acquisition cost can encourage groundwater irrigation in Africa, even for smallholders. In fact, small private irrigation (or individual irrigation) is a growing trend in the nations of SAA (De Fraiture and Giordano, 2014) and some argue that minor irrigation projects perform better than large-scale projects (Fujiie et al., 2011). However, the growth of small irrigation is spontaneous and unregulated (De Fraiture and Giordano, 2014) which poses environmental issues, especially in the context of low cost or free energy access. India is a typical example of a nation that provides subsidized electricity, which encouraged unsustainable groundwater irrigation development and extraction, negatively impacting the groundwater resource to the point of depletion (Fishman et al., 2016).

4.2.4.4 Limitations of approach

Our methodology considers that groundwater is usable and available. Groundwater is generally good water quality since it is naturally protected from human pollution. However, natural chemistry mechanisms between the water and underground minerals can affect the groundwater quality primarily controlled by the geology; this is particularly significant in the African Rift where groundwater can have high salinity and even high fluoride and arsenic concentrations. In the context of groundwater development for irrigation, water treatment is too expensive for agricultural use, thus reducing groundwater availability.

Finally, the methodology does not take into consideration some driving factors which are complicated to address quantitatively at a country scale and even more difficult at a local level. National policies, public/NGO investment, institutions and services to farmers can promote irrigation development by incentivising farmers to invest in irrigation and by providing financing and better information to farmers. An example is the incentives for the adoption of new technology and public investment policies in India during the 1970s – 1990s which spurred the growth of boreholes (Dev, 2012) and partly induced several groundwater issues such as the current groundwater depletion (Aeschbach-Hertig and Gleeson, 2012). Also, a lack of secure land tenure can constraint investment (Villholth, 2013). While local situations concerning land tenure are complex (e.g., customary right), Woodhouse et al. (2017) provided several examples throughout Africa where farmers with insecure land tenure invested in irrigation. In fact, small private irrigation has been developing quickly in South Asia, and it is now emerging in SSA; this corresponds to farmer-led irrigation development when farmers overcome some barriers to irrigation development. The "under the radar" and uncounted areas under privately managed and owned irrigation can be more extensive than public schemes in some countries (De Fraiture and Giordano, 2014; Woodhouse et al., 2017). In this context, return on investment and access to financing are critical to farmers investing in their irrigation systems. In fact, micro-financing for rural smallholders has been identified as having significant potential in Africa. Direct grants or public loans are often out of reach for rural farmers (Villholth, 2013) and well-functioning domestic markets in combination with good rural infrastructure, appropriate institutions, and access to appropriate technology are vital to increasing agricultural productivity, and thus the attractiveness of irrigation (Pinstrup-Andersen and Shimokawa, 2006). Smallholders' willingness to invest, policies and services to farmers, and appropriate investment conditions (e.g., a functioning market, rural infrastructure, and access to capital) play an important role in groundwater irrigation development, but it must be undertaken sustainably to limit the impact of anarchic groundwater development.

4.2.5 Conclusion

This study is the first continental study using socio-economic and biophysical driving factors pertinent to groundwater irrigation development with quantitative hydrological data for identifying and quantifying those areas where it is worthwhile to develop groundwater irrigation further. Results show spatial variation across the continent and within the countries.

First, the present study displayed the extent and distribution of the conduciveness of groundwater irrigation development (GIDD) across the African continent (0.005-degree resolution) based on six driving factors related to groundwater irrigation development. The overall GIDD is displayed in five conduciveness classes (extremely, highly, moderately, slightly and non-conducive). Results show that areas, where groundwater irrigation development could be developed, are located along a west-east stripe going from Senegal and Guinea to Ethiopia and a large North-south-west stripe from Ethiopia to Zimbabwe and Angola. There are no significant extremes for the conduciveness classes with most of the cells ranging from highly to slightly conductive. Extremely and highly conducive areas are found at the proximity of intermittent rivers and between perennial rivers when there is a shallow aquifer, particularly along the Sahel, the South of Somalia, and in South Africa. Non-conducive areas are primarily located in pockets at the border of Chad and Central African Republic (CAR), in the Ethiopian highlands, and at the border of Angola, Botswana and Namibia where there is low population density and a deeper aquifer.

Second, this study redistributes the GIRP calculated by Altchenko and Villholth (2015) into the extremely and highly conducive classes of the GIDD. The resulting GIDP estimates to 19.3 x 10^6 ha the amount of cropland that is worthwhile to develop with groundwater irrigation. The result represents approximately 43% of the previous estimate resulting from the quantitative hydrological approach. Most of the missing land is located in the equatorial region of Central Africa where irrigation demand is low. GIDP is estimated to be about nine times the current area equipped for groundwater irrigation in Africa. However, when considering countries where the sustainable groundwater irrigation potential is not already exhausted, the areas irrigable with sustainable groundwater are 75 times more important than the current irrigated areas. The main GIDP is located along a west-east line from Angola to the North of Mozambique and along a west-east line southern to the Sahel. The highest development potential (higher than 2 ha per cell) is found in some pockets in the Ivory Coast, the extreme south of Mali, Tanzania, Zambia and the West of Ethiopia. Results also indicate that sustainable groundwater irrigation development should focus on smallholders (less than 1 to 2 hectares), and on very smallholders (less than 0.2 hectares) in the semi-arid Sahel, Eastern Africa and Southern Africa region where the development of groundwater irrigation could level up livelihoods by providing food production from reliable and affordable water resources.

The sensitivity analysis reveals that groundwater availability (A) and crop water need (B) are the dominant driving factors and that results might have been overestimated because of the ranking of the parameters used for the access to surface water (A). However, results are particularly robust in the arid areas (i.e., the Sahel, Horn of Africa and Southern Africa).

Finally, there is a need to increase the resilience and adaptive capabilities of the nations to respond to increased stress on water resources (both surface and groundwater), in the context of climate trends, population growth, and increases in water demand for domestic or agricultural uses. Strategies to improve water efficiency including increasing water storage (i.e., artificial recharge) must be investigated. Such investigation assumes financial capacity, which can be limited for African countries, especially in SSA. However, it is estimated that the annual cost of climate change adaptation ranges from $20 to 30 billion (USD) over the next 10 to 20 years (AfDB and AfDF, 2011). This cost represents about 1.3-1.4% of the African GDP which is a higher percentage than in other regions of the world. Groundwater irrigation and its development in Africa could benefit from this climate adaption cost.

5 Conclusion and ways forward

In the African context of population growth, eradication of hunger and uncertainty of the impact of climate change on rainfall, groundwater irrigation is considered a reliable and affordable means to increase food security. Areas equipped for groundwater irrigation in Africa have however, developed slowly since 1950 and remain very limited. To date, no studies have identified the sustainable development potential of irrigation with renewable groundwater across Africa. This thesis aims to locate and quantify those areas where croplands are worthwhile to sustainably develop with groundwater irrigation to determine the sustainable groundwater irrigation development potential of Africa. The methodology used for this thesis is based on two mapping approaches.

The first approach corresponds to quantitative groundwater irrigation potential. The continent-wide analysis (0.5-degree spatial resolution, about 50 x 50 km cell) defines the water resource for irrigation as the fraction of groundwater recharge above current human needs and environmental requirements, without regard for the socioeconomic and biophysical factors that influence access to the resource. Due to the considerable uncertainty of groundwater environmental needs, three scenarios were considered leaving 30%, 50% and 70 % of the recharge for the environment. The study aggregated dominant crops into six groups (cereal, pulse, root, oil, vegetable and sugarcane) with crop rotations and associated irrigation requirements (i.e., the additional water needed to attain optimal growth of the crop after naturally available water from rain and soil moisture are absorbed) applied in a zonal approach to convert recharge excess into potentially irrigable cropland areas. Irrigation requirements were based on climatic conditions and crop water requirements to achieve optimal growth. Results show that up to 105.3 x 10^6 ha of croplands can be irrigated with groundwater, depending on the three scenarios and disregarding existing irrigation. The most conservative scenario (70% of the recharge returns to the environment, meaning that a portion of the remaining 30% will be available for irrigation after satisfying all other needs such as drinking water supply, industrial needs, and livestock watering) estimates that 44.7 x 10^6 ha of croplands can be irrigated with sustainable groundwater (GIRP map). That corresponds to 20.5% of the cropland over the continent. While existing groundwater irrigation development is primarily located in North Africa and Southern Africa where the sustainable potential is limited, there is untapped potential in Eastern Africa and the Sahel region that could significantly improve food security in Africa.

The second approach corresponds to environmental groundwater irrigation potential. The continent-wide analysis (0.005-degree special resolution, about 0.5 x 0.5 km cell) first identifies the driving factors that constrain or are conducive to groundwater irrigation development. The identified driving factors are: groundwater availability, crop water need, access to surface water, access to market, terrain suitability for agriculture and the borehole investment. The analysis maps each driving factors of groundwater irrigation development to determine the distributed individual groundwater irrigation development driver map for each driving factor. It then combines the partial groundwater irrigation development drivers maps through a composite mapping analysis in GIS using different weighting methods to extract the highest constraint from each result of the various weighting methods to determine the irrigation development obstacles (GIDD). The results indicate that areas are less conducive to groundwater irrigation development in arid regions with low population density than regions with perennial rivers. Globally, slight and no conduciveness is found mainly in arid areas with low population density, weak road networks, and poor terrain suitability. There is moderate conduciveness in the vicinity of perennial rivers while extreme and high conduciveness are located between perennial rivers and in the vicinity of intermittent rivers zones, with two visible corridors with high conduciveness appearing in the Sahel region and the South-eastern area of the Kalahari.

The two approaches are combined to map the sustainable groundwater irrigation development potential (GIDP). This corresponds to the GIRP areas which are conducive to groundwater irrigation development. Results estimate that 19.3 x 10^6 ha could be sustainably developed across Africa, which represents an eightyfold increase over existing groundwater irrigation on the continent. When excluding the Maghreb region and South Africa where GIDP is already exhausted, areas irrigable with sustainable groundwater represent a 75fold increase over currently irrigated land. The largest areas which are worthwhile to develop are mainly located along a west-east line from Angola to the north of Mozambique and a line south of the Sahel. There is some uncertainty on the results in these regions while results are robust in the dry regions of the Sahel, East Africa and Southern Africa which have limited development potential, more suitable to small-scale agriculture. Not surprisingly, the thesis indicates that results are highly dependent on the crop water needs and the availability of sustainable groundwater for irrigation needs.

This thesis is the first continental study using qualitative socio-economic and biophysical approaches and a quantitative hydrological approach for identifying areas with the potential for developing sustainable groundwater irrigation. It shows that there is an important potential in Africa to develop sustainable groundwater irrigation development with reliable and sustainable groundwater irrigation development. That significantly improves smallholder livelihoods by increasing crop production, productivity, and food security. It displays the spatial variation across the continent and within the countries.

However, the author would like to add a warning about the use of the results from this study. Results cannot be used for direct implementation of groundwater irrigation development and investment due to the assumptions made when the methodology was developed. This study could be used by communities, NGOs or governments as a tool for prioritizing local investigations into groundwater irrigation development feasibility within countries. Variation of the local hydrogeology conditions and environment need to be assessed in order to determine the quality, quantity and renewability of the groundwater resource. The local socio-economics conditions which could be condutive to groundwater irrigation development need also to be identified.

During this study, several opportunities for additional research emerged:

- **Down-scaling, improving and adapting the methodology to local conditions**: it is believed that the methodology could be applied, modified and enhanced at the country scale (or smaller) with additional driving factors and a more detailed database. For example, one additional factor could be groundwater quality which was disregarded during the analysis because of the lack of information at the continental scale. Groundwater quality could be added as a limiting factor because local data might exist. In fact, while groundwater is usually of good quality, saline groundwater, which cannot be used for irrigation purposes, is common in the East Africa Rift zone and coastal areas. Additional factors could include the type and cost of energy used by lifting devices and the level of opportunities for smallholders to invest in groundwater irrigation.

- **Estimating food production potential from groundwater irrigation**: research work can be performed by translating the areas that can be developed with sustainable groundwater irrigation to an estimate of food production. Databases such as the Global Agro-ecological Zones (GAEZ) provide information about the yield per type of crop under rainfed and irrigated conditions. By comparing yields and the areas that can be developed, an estimate of additional crop production could be produced; this means that further work should be done on crop irrigation requirements as the crops have been aggregated into six groups. There is probably a need to adapt the methodology for each crop. The research could also be linked with international food trade in Africa to better understand the impact of additional food production from groundwater irrigation on the continent's food security.

- **Recharge changes due to climate change**: the availability of sustainable groundwater is the most limiting factor for developing groundwater irrigation. This thesis is based on hydrological data from the PCR-GLOBWB global hydrological model (Van Beek et al., 2011; Wada et al., 2011) which provides daily data for a 41-year period (January 1960 to December 2000). However, recharge is highly dependent on climate, and the impacts on recharge due to climate change can be significant in both quality and quantity (Bonsor and Macdonald, 2010; Meixner et al., 2016; Moseki, 2017; Kahsav et al. 2018). Thus, it would be interesting to use the methodology with projected data on recharge over the continent or on a more local scale.

- **Transboundary aquifer hot spots**: groundwater irrigation development should be sustainable and equitable among countries. Riedel and Döll (2015) identified ten transboundary aquifer hotspots in Africa where at least one country experienced development stress because of human dependence on groundwater. Six of the ten hotspots are in areas identified with sustainable groundwater irrigation development potential. New research could focus specifically on these transboundary areas to re-estimate the sustainable groundwater irrigation development potential to prevent future conflicts among nations.

6 References

ADB (2013) Thinking about water differently: Managing the water-food-energy nexus. Asia Development Bank (ADB), Mandaluying City.

ADB, FAO, IFAD, IWMI and World Bank (2007) Investment in Agricultural Water for Poverty Reduction and Economic Growth in Sub-Saharan Africa, Synthesis Report, available at http://siteresources.worldbank.org/RPDLPROGRAM/Resources/459596-1170984095733/synthesisreport.pdf (last access: 01 September 2018).

Adhikari, U., Nejadhashemi, A. P. and Woznicki, S. A. (2015) Climate change and eastern Africa: a review of impact on major crops, Food and Energy Security, Volume 4, Issue 2, pp 110-132.Aeschbach-Hertig, W. and Gleeson, T. (2012) Regional strategies for the accelerating global problem of groundwater depletion. Nature Geoscience, Issue 5, pp. 853-861.

AfDB and AfDF (2011) The Cost of Adaptation to climate Change in Africa. African Development Bank and African Development Fund, available at https://www.afdb.org/fileadmin/uploads/afdb/Documents/Project-and-Operations/Cost%20of%20Adaptation%20in%20Africa.pdf (last access: 01 august 2018).

Alexandros, N. and Bruinsma, J. (2012) World agriculture towards 2030/2050: the 2012 revision. FAO, Rome.

Altchenko, Y. and Villholth, K. G. (2015) Mapping irrigation potential from renewable groundwater in Africa – a quantitative hydrological approach. Hydrol. Earth Syst. Sci., Volume 19 (2), pp. 1055-1067.

Arauzo, M. and Martínez-Bastida, J.J. (2015) Environmental factors affecting diffuse nitrate pollution in the major aquifers of central Spain: groundwater vulnerability vs. groundwater pollution, Environ. Earth Sci., Volume 73, pp. 8271–8286.

AU (2014) Malabo Declaration on Accelerated Agricultural Growth and Transformation for Shared Prosperity and Improved Livelihoods. Available at: http://pages.au.int/sites/default/files/Malabo%20Declaration%202014_11%2026-.pdf (last access: le 01 august 2018).

AU, ECA, ADB and UNDP (2017) Africa Sustainable Development Report: Tracking Progress on Agenda 2063 and the Sustainable Development Goals, African Union (AU), Economic Commission for Africa (ECA); African Development Bank (ADB) and United Nations Development Programme (UNDP), Addis Ababa.

Awulachew, S. B., Erkossa, T. and Namara, R. E. (2010) Irrigation potential in Ethiopia: Constraints and opportunities for enhancing the system. International Water Management Institute, Colombo.

Balk, D., Deichmann, U., Yetman, G., Pozzi, F., Hay, S. I. and Nelson A. (2006) Determining Global Population Distribution: Methods, Applications and Data. Advances in Parasitology, Volume 62, pp. 119-156.

Barica, J. (1972) Salinization of groundwater in arid zones, Water research, Volume 6, Issue 8, pp. 925-933.

Beegle, K., Christiaensen, L., Dabalen, A. and Gaddis, I. (2016) Poverty in a Rising Africa. World Bank, Washington.

Berahmani, A., Faysse, N., Errahj, M. and Gafsi, M. (2012) Chasing water: diverging farmers' strategies to cope with the groundwater crisis in the coastal chaouia region in morocco. Irrigation and Drainage, Volume 61, Issue 5, pp. 673-681.

Bonsor H. C. and Macdonald A. M. (2010) Groundwater and climate change in Africa: review of recharge studies. Internal Report IR/10/075, British Geological Survey.

Bonsor, H. C. and MacDonald, A. (2011) An initial estimate of depth to groundwater across Africa. Open Report, British Geological Survey, Keyworth.

Bryceson, D., Sarkar, P., Fennel, S. and Singh, A. (2010) Globalisation, Structural, Adjustment and African Agriculture: analysis and evidence, Working paper No. 414, Center for Business, University of Cambridge, Cambridge.

Burke, J. J., Sauveplane, C. and Moench, M. (1999) Groundwater management and socio-economic responses. Natural Resources Forum, Volume 23, pp. 303-313.

CAADP (2009) Sustainable Land and Water Management, The CAADP Pillar I Framework. Available at www.nepad.org/download/file/fid/6324%20 (last access: 21 May 2015).

Calow, R. C. et al. (1997) Groundwater management in drought-prone areas of Africa. International Journal of Water Resources Development, Volume 13, pp. 241-261.

Calow, R., MacDonald, A., Nicol, A. and Robins, N. (2010) Ground Water Security and Drought in Africa: Linking Availability, Access, and Demand. Ground Water, Volume 48 (2), pp. 246-256.

Chamberlin, J., Jayne, T. and Headey, D. (2014) Scarcity amidst abundance? Reassessing the potential for cropland expansion in Africa. Food policy, Volume 48, pp. 51-65.

Christiaensen, L., Demery, L. and Kuhl, J. (2011) The (evolving) role of agriculture in poverty reduction-an empirical perspective. J. Dev. Econ, Volume 96 (2), pp. 239-254.

De Fraiture, C. and Giordano, M. (2014) Small private irrigation: a thriving but overlooked sector. Agriculture Water Management, Volume 13, pp. 167-174.

DESA (2013) World Economic and Social Survey 2013: Sustainable Development Challenges, United Nations, New York.

DESA (2014) World urbanization Prospect: the 2014 revisions, Highlights. United Nations, New York.

DESA (2015) World Population Prospects, The 2015 revision: Key findings and advance tables. United Nations, New York.

De Stefano, L. and Lopez-Gunn, E. (2012) Unauthorized groundwater use: institutional, social and ethical consideration, Water Policy, Volume 14, pp 147-160.

Dev, S. M. (2012) Small Framers in India: Challenges and opportunities, Indira Gandhi Institute of Development Research, Mumbai.

Diabene, P. Y. and Gyamfi, C. (2014) Groundwater potential for rural water supply: a sustainably assessment of borehole in the Bawku West district, Ghana. Journal of Environmental Science and Water Resources, Volume 3 (5), pp. 110-117.

Diao, X., Hazell, P. and Thurlow, J. (2010) The Role of Agriculture in African Development. World Development, Volume 38 (10), pp. 1375-1383.

Döll, P. and Fiedler, K. (2008) Global-scale modelling of groundwater recharge. Hydrol. Earth Syst. Sci., Volume 12, pp.863–885.

Doll, P., H. Muller Schmied, C. Schuh, F. T. Portmann, and A. Eicker (2014) Global-scale assessment of groundwater depletion and related groundwater abstractions: Combining hydrological modelling with information from well observations and GRACE satellites, Water Resour. Res., Volume 50, pp. 5698–5720, doi:10.1002/2014WR015595.

Domènech, L. (2015) Improving irrigation access to combat food insecurity and undernutrition: A review, Global Food Security, Volume 6, pp. 24-33.

Droogers, P., Seckler, D. and Ian Makin I. (2001) Estimating Potential Rain-fed Agriculture, Working Paper 20, International Water Management Institute (IWMI), Colombo.

Droogers, P., e Nkurunziza, P., Bastiaanssen, W., Immerzee, W., Terink, W., Hunink, J., Meijninger, W., Hellegers, P., Chevalking, S., Steenbergen, F. and Brandsma, J. (2012) Assessment of the irrigation potential in Burundi, Eastern DRC, Kenya, Rwanda, South Sudan, Tanzania and Uganda. Report FutureWater:114, Wageningen.

Department of Water Affairs (2013) Republic of South Africa - National Water Resource Strategy: Water for an Equitable and Sustainable Future. Available at http://cer.org.za/wp-content/uploads/2013/07/NWRS2-Final-email-version.pdf (last access le 01 august 2018).

Evans, W. R., Evans, R. S., and Holland, G. F. (2012) Conjunctive use and management of groundwater and surface water within existing irrigation commands: the need for a new focus on an old paradigm. Thematic Paper 2, Groundwater Governance: A Global Framework for Country Action, GEF ID 3726, 48 pp.

Evenson, R. E. and Gollin, D. (2003) Assessing the impact of Green revolution 1960 to 2000. Science, Volume 300, pp. 758-762.

FAD and UNESCO (1974) Soil map of the world, scale 1: 5000000. FAO, Rome.

Fageria, N. K., Baligar, V. C. and Jones C., A. (2010) Growth and mineral nutrition of field crops. CRC Press, Editors: Boca Raton, Taylor & Francis Group, LLC.

Falkenmark, M. (1995) Coping with water scarcity under rapid population growth. Conference of SADC Ministers, Pretoria, pp. 23-24.

Falkenmark, M. and Rockström, J. (2006) The new blue and green water paradigm: Breaking new ground for water resources planning and management. J. Water Resour. Plann. Manage., Volume 132, pp. 129–132.

FAO (1986) Irrigation Water Management: Irrigation Water Need. In: Brouwer, C. and Heibloem, M. (Eds) Training Manual no. 3, Food and Agriculture Organization of United Nations, Roma.

FAO (1989) Irrigation Water Management: Irrigation Scheduling, In: Brouwer, C., Prins, K., and Heibloem (Eds) Training Manual no. 4, Land and Water Development Division, FAO, Roma.

FAO (1992) Crop Water Requirements, In: Doorenbos, J., Pruitt, W. O., Aboukhaled, A., Damagnez, J., Dastane, N. G., Van den Berg, C., Rijtema, P. E., Ashford, O. M., and Frere, M. (Eds) FAO Irrigation and Drainage Paper no. 24, Land and Water Development Division, FAO, Roma.

FAO (1996) Rome Declaration on World Food Security and World Food Summit Plan of Action. Available at: http://www.fao.org/docrep/003/w3613e/w3613e00.HTM (last access: 01 August 2018).

FAO (1997) Irrigation Potential in Africa: A Basin Approach, FAO Land and Water Bulletin 4, Land and Water Development Division, FAO, Roma.

FAO (2003) Trade reforms and food security - conceptualizing the linkages. FAO, Roma.

FAO (2005) Irrigation in Africa in Figures, AQUASTAT Survey – 2005, Frenken, K. (Eds), FAO Water Reports no. 29, FAO, Roma, available at: https://www.researchgate.net/publication/235704388_Irrigation_in_Africa_in_figures_AQUASTAT_survey_2005 (last access: 20 May 2018)

FAO (2007a) Population density (persons/km2), Available at: http://www.fao.org/geonetwork/srv/en/resources.get?id=30586&fname=poprecl_ASCII.zip&access=private (last access: 31 March 2018)

FAO (2007b) Gridded livestock of the world. Available at: http://www.fao.org/ag/againfo/resources/en/glw/GLW_dens.html (last access: 31 March 2018)

FAO (2008) An Introduction to the Basic Concepts of Food Security. EC - FAO Food Security Program.

FAO (2015) Regional overview of food insecurity: Africa food security prospects brighter than ever. FAO, Accra.

FAO and ICRISAT (2015) Community Seed Production, by Ojiewo C. O., Kugbei S., Bishaw Z. and Rubyogo JC, eds. Workshop Proceedings, 9-11 December 2013. FAO, Rome and ICRISAT, Addis Ababa. 176 pp.

FAO, IFAD and WFP (2014) The State of Food Insecurity in the World 2014. Strengthening the enabling environment for food security and nutrition. FAO, Roma.

FAO, IFAD and WFP (2015) The state of food insecurity in the world 2015. Meeting the 2015 international targets: taking stock of uneven progress. FAO, Roma.

FAO/IIASA/ISRIC/ISS-CAS/JRC (2012) Harmonized World Soil Database (version 1.2), FAO, Rome, Italy and IIASA, Laxenburg, Austria.

Fischer, R. A., Byerlee, D. and Edmeades, G. O. (2014) Crop yields and global food security: will yield increase continue to feed the world? ACIAR Monograph No. 158. Australian Centre for International Agricultural Research, Canberra.

Fisher, G. and Shah, M. (2010) Farmland investment and food security, World Bank Washington. Available at , http://documents.worldbank.org/curated/en/884731468221080363/Farmland-investments-and-food-security (last access: 01 August 2018).

Fishman, R., Lall, U. and Modi, V. P. N. (2016) Can Electricity Pricing Save India? Field Evidence from a Novel Policy Mechanism in Gujarat. JARERE, Volume 3 (4).

Forkuor, G., Pavelic, P., Asare, E. and Obuobie, E. (2013) Modelling potential areas of groundwater development for agriculture in North Ghana using GIS/RS. Hydrological Sciences Journal, Volume 58 (2), pp. 437-451.

Fornes, J., De La Hera, A. and Llamas, M, R (2005) The silent revolution in groundwater intensive use and its influence in Spain. Water Policy, Volume 7 (3), pp. 253-268.

Foster, S. and Perry, C. (2010) Improving groundwater resource accounting in irrigated areas: a prerequisite for promoting sustainable use. Hydrogeol. J., Volume 18, pp. 291–294

Foster, S., Chilton, J., Moench, M., Cardy, F. and Schiffer, M (2008) Groundwater in rural development: Facing the challenges of supply and resource sustainability. Working Technical Paper No. 463, World Bank, Washington D.C.

Frenken, K. (2005) Irrigation in Africa in Figures, AQUASTAT Survey – 2005, FAO, Roma, available at: https://www.researchgate.net/publication/235704388_Irrigation_in_Africa_in_figures_AQUASTAT_survey_2005 (last access: 20 May 2018)

Fujiie, H., Maruyama, A., Fujiie, M., Takagaki, M., Merrey D. J. and Kikuchi, M. (2011) Why invest in minor projects in sub-Saharan Africa? An exploration of the scale economy and diseconomy of irrigation projects. Irrig Drainage Syst, Volume 25, pp. 39-60.

Funk C., Hoell A., Shukla S., Husak G., Michaelsen J. (2016) The East African Monsoon System: Seasonal Climatologies and Recent Variations. In: de Carvalho L., Jones C. (eds) The Monsoons and Climate Change. Springer Climate. Springer, Cham.Gan, T. Y., Ito, M., Hulsmann, S., Qin, X., Lu, X. X., Liong, S. Y., Rutschman, P., Disse, M. and Koivusalo, H. (2015) Possible climate change/variability and human impact, vulnerability of African drought prone regions, its water resources and capacity building. Hydrological Sciences Journal, Volume first online available at http://dx.doi.org/10.1080/02626667.2015.1057143 (last access 01 august 2018).

Gan, T.Y., Mari Ito, M., Hülsmann, S., Qin, X. Lu, X.X., Liong, S.Y., Rutschman, P., Disse, M. and Koivusalo H. (2016) Possible climate change/variability and human impact, vulnerability of African drought prone regions, its water resources and capacity building. Hydrological Sciences Journal, Volume 61, Issue 7, pp 1209-1226.

Garduño, H. and Foster, S. (2010) Sustainable Groundwater Irrigation approaches to reconciling demand with resources, Washington: GW-MATE.

Godfray, C. J., Beddington, J. R., Ian R. Crute, I. R.; Haddad, L., Lawrence, D., Muir, J. F., Pretty, J., Robinson, S., Thomas, S. M., Toulmin, C. (2010) Food Security: The Challenge of Feeding 9 Billion People, Science, Volume 327, Issue 5967, pp. 812-818.

Grafton, R. Q., Daugbjerg, C. and Qureshi, M. E. (2015) Toward food security by 2050, Food Security, Volume 7, Issue 7, pp 179-183.

Gumma, M. K. and Pavelic, P. (2013) Mapping of groundwater potential zones across Ghana using remote sensing, geographic information systems, and spatial modelling. Environmental monitoring and assessment, Volume 185(4), pp. 3561-3579.

Haverkort, A. J. and Schapendonk, A. H. (1994) Crop reactions to environmental stress factors. In: P. Struik, W. J. Vredenberg, J. A. Renkenma and J. E. Parlevliet, eds. Plants production on the threshold of a New Century. Development in plants and soils sciences ed. Springer, Dorfrecht.

Hermann, S., Miketa, A. and Fichaux, N. (2014) Estimating the Renewable Energy Potential in Africa, IRENA-KTH working paper, International Renewable Energy Agency, Abu Dhabi.

IFPRI (2012) Regional analysis of treadle pumps: Potential for expansion in Sub-Saharan Africa, International Food Policy Research Institute (IFPRI), Washington.

IFPRI (2014) Atlas of African Agriculture Research & Development: revealing agriculture’s place in Africa, Sebastia, K. (Eds), International Food Policy Research Institute (IFPRI), Washington.

Inocencio, A., Sally, H. and Merrey, D. J. (2003) Innovative approaches agricultural water uses for improving food security in Sub-Sahara Africa. IWMI Working Paper 055, International Water Management Institute, Colombo.

IRENA, 2016. Solar pumping for irrigation: Improving livelihoods and sustainability, International Renewable Energy Agency, Abu Dhabi.

IWMI (2007) Water for Food, Water for Life: a comprehensive assessment of water management in agriculture. IWMI/Earthscan ed. Colombo: IWMI/Earthscan.

Jamin, J.-Y., Bouarfa, S. and Poussin, J.-C. G. P. (2011) Les agricultures irriguées face à de nouveaux défis. Cah Agric, Volume 20 (1-2), pp. 10-15.

Jayne, T., Chamberlin, J. and Headey, D. D. (2014) Land pressures, the evolution of farming systems, and development strategies in Africa: A synthesis. Food policy, Volume 48, pp. 1-7.

Kajander, T., Varis, O. and Rahaman, M. (2002) Driving forces behind the groundwater degradation – a comparative analysis on three developing macro-regions in Asia. Islamabad, Pakistan, pp. 283-295.

Kanu, B. S., Salami, A. O. and Numasawa, K. (2014) Inclusive growth: an imperative for Africa Agriculture. African Development Bank (AfDB) Group, Tunis.

Kottek, M., Grieser, J.; Beck, C., Rudolf, B., Rubel, F. (2006) World Map of the Köppen-Geiger climate classification updated. Meteorologische Zeitschrift, Volume 15(3), pp. 259-263.

Kuper, M., Faysse, N., Hammani, A., Hartani, T., Marlet, S., Hamamouche, M. F., and Ameur, F. (2016) Liberation or Anarchy? The Janus nature of groundwater use on North Africa’s new irrigation frontiers. In. A. Jakeman, O. Barreteau, R. Hunt, J. D. Rinaudo, and A. Ross (Eds.), Integrated groundwater management: Concepts, approaches and challenges (pp. 583–615). Springer: Dordrecht,

Lee, J.-Y. and Song, S.-H. (2007) Evaluation of groundwater quality in coastal areas: implications for sustainable agriculture. Environmental Geology, Volume 52, Issue 7, pp. 1231-1242.

Lehner, B., Verdin, K. and Jarvis, A. (2008) New global hydrography derived from spaceborne elevation data. Eos, Transactions, AGU, Volume 89 (10), pp. 93-94.

Lodwick, W. A., Monson, W. and Svoboda, L. (1990) Attribute error and sensitivity analysis of map operations in geographical information system: suitability analysis. International Journal of Geographical Information Systems, Volume 4 (4), pp. 413-428.

Lopez-Gunn, E., De Stefano, L. and Llamas, M. (2012) The role of ethics in water and food security: balancing utilitarian and intangible values. Water Policy, Volume 14, pp 89-105.

Lowry, J. H. J., Miller, H. J. and Hepner, G. F. (1995) A GIS-based sensitivity analysis of community vulnerability to hazardous contaminants on the Mexico/U.S. border. Photogrammetric Engineering & Remote Sensing, Volume 61 (11), pp. 1347-1359.

MacDonald, A. M. and Davies, J. (2000) A brief review of groundwater for rural water supply in sub-Saharan Africa. BGS Technical Report British Geological Survey, Keyworth.

MacDonald, A. M. and Calow, R. C. (2009) Developping groundwater for secure rural water supplies in Africa. Desalinisation, Volume 248, Issues 1-3, pp. 546-556.

Macdonald, D M J, Thompson, D M and Herbert, R (1995) Sustainability of yield from wells and boreholes in crystalline basement aquifers. Technical Report WC/95/50, British Geological Survey, Keyworth.

MacDonald, A. M., Bonsor, H. C., Dochartaigh, B. É. Ó. and R G Taylor, R. G. (2012) Quantitative maps of groundwater resources in Africa. Environ. Res. Lett, Volume 7 (2), p. 7.

MacDonald, A. M., Calow, R. C., Nicol, A. L., Hope, B. and Robin, N. S. et al. (2001) Ethiopia: water security and drought. Technical Report WC/01/02, British Geological Survey, Nottingham.

MacDonald, A. M., Taylor, R. G. and Bonsor, H. C. (2013) Groundwater in Africa - is there sufficient water to support the intensification of agriculture from 'land grabs'? In: T. Allan, M. Keulertz, S. S. and J. Warner (eds) Handbook of Land and Water Grabs in Africa - Foreign direct investment and food and water security, pp. 376-384, Routledge, Abingdom.

Madramooto, C. (2012) Sustainable groundwater use in Agriculture, Groundwater Governance: Learning from local experiences, Volume 61, Issue S1, pp26-33.

Malczewski, J. (1999) GIS and Multicriteria Decision Analysis. John Wiley & Sons, New York.

Margat, J. (2010) Ressources et utilisation des eaux souterraines en Afrique, In: Managing Shared Aquifer Resources in Africa, Third International Conférence Tripoli 25-27 may 2008, IHP-VII Series on groundwater No., International Hydrological Programme, Division of Water Sciences, UNESCO, Paris.

Margat, J. and Van der Gun, J. (2013) Groundwater Around the World: A Geographic Synopsis. CRC Press, Taylor & Francis Group, London.

Meixner, T., Manning, A. T., Stonestrom, Diana, D. A., Allen, M., Ajami, H., Blasch, Brookfield, A. E., Castro, C. L., Clark, J. F., Gochis, D. J., Flint, A. L., Neff, K. L., Niraula, R., Rodell, M., Scanlon, B. R., Singha, K. and Walvoord, M.A. (2016) Implications of projected climate change for groundwater recharge in the western United States. Journal of Hydrology, Volume 534, pp.124-138.

MINEAU (2010) Etude de Faisabilite des Forage Manuels Identification des Zones. Available at https://www.unicef.org/french/wash/files/MADAGASCAR_Raport_final_forges_manuels_(FINAL).pdf (last access: 01 august 2018)

Ministry of Agriculture (2004) The Republic of Zambia: National Agriculture Policy 2004/2015. Available at http://gafspfund.org/sites/default/files/inline-files/5.%20Zambia_strategy.pdf (Last access: 21 May 2018).

Ministry of Finance and Economic Development (2010) The Federal Democratic Republic of Ethiopia: Growth and Transformation Plan (GTP) 2010/11–2014/15 Draft. Available at https://theredddesk.org/sites/default/files/growth_and_transformation_plan.pdf (last access: 21 May 2018).

Ministry of Food and Agriculture (2011) National Irrigation Policy, Strategies and Regulatory Measures, Ministry of Food and Agriculture (MoFA), Accra. Available at http://mofa.gov.gh/site/wp-content/uploads/2011/07/GHANA-IRRIGATION-DEVELOPMENT-POLICY1.pdf (Last access: 21 May 2018).

Ministry of Irrigation and Water Development (2005) The Republic of Malawi: National Water Policy 2005. Available at: https://cepa.rmportal.net/Library/government-publications/National%20Water%20Policy%202005.pdf/at_download/file (Last access on 21 May 2018).

Monfreda, C., Ramankutty, N, and Foley, J. A. (2008) Farming the planet: 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000. Global Biogeochem. Cy., Volume 22,

Montz, B. E. and Evans, T. A. (2001) GIS and social vulnerability analysis. In: E. Gruntfest and J. W. Handmer (eds) Coping with Flash Floods, pp. 37-48, Kluwer Academic, Dordrech.

Moseki, M. C. (2017) Climate change impacts on groundwater: literature review. Environmental Risk Assessment and Remediation, Volume 2 (1), pp 16-20.

MoWEA (2013) The Republic of South Africa: National Water Resource Strategy, June 2013, Second Edition, Department of Water Affairs. Available at http://www.dwa.gov.za/documents/Other/Strategic%20Plan/NWRS2-Final-email-version.pdf (last access: 21 May 2018).

Mueller, N. D., Gerber, J. S., Johnston, M., Ray, D. K., Ramankutty, N. and Foley, J. A. (2012) Closing yield gaps through nutrient and water management. Nature, Volume 490, pp. 254-257.

Narayan, K. A., Schleeberger, C. & Bristowa, K. L., 2007. Modelling seawater intrusion in the Burdekin Delta Irrigation Area, North Queensland, Australia. Agricultural Water Management, Volume (89), Issue 3, pp. 217-228.

Nellemann, C. MacDevette, M., Manders, T., Eickhout, B., Svihus, B., Prins, A. G., and Kaltenborn, B. P. (Eds) (2009) The environmental food crisis - The environment's role in averting future food crises. United Nations Environment Programme, GRID-Arendal.

NEPAD (2003) Comprehensive Africa Agriculture Development Programme. Available at http://www.fao.org/nr/water/aquastat/sirte2008/NEPAD-CAADP%202003.pdf (Last access: 21 May 2018).

NEPAD, UNZA, and CILS (2009) Sustainable Land and Water Management, The CAADP Pillar I Framework. Available at: http://www.nepad.org/download/file/fid/6323 (last access: 01 august 2018).

Neumann, K., Stehfest, E., Verburg, P. H., Siebert, S., Muller, C. and Veldkamp, T. (2011) Exploring global irrigation patterns: A multilevel modelling approach. Agricultural Systems, Volume 104 (9), pp. 703-713.

Ngaira J. K. W. (2007) Impact of climate change on agriculture in Africa by 2030, Scientific Research and Essays, Volume 2, Issue 7, pp. 238-243.

Niang, I., O.C. Ruppel, M.A. Abdrabo, A. Essel, C. Lennard, J. Padgham, and P. Urquhart (2014) Africa. In: Barros, V.R., C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.) Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, pp. 1199-1265, Cambridge University Press, Cambridge and New York, NY, USA.

Nicholson, S. (2013) The West African Sahel: A Review of Recent Studies on the Rainfall Regime and Its Interannual Variability, ISRN Meteorology, Volume 2013.

Nin-Pratt, A. and McBride, L. (2014) Agricultural intensification in Ghana: Evaluating the optimist's case for green Revolution. Food policy, Volume 48, pp. 153-167.

Oates, N., Jobbins, G., Mosello, B. and Arnold j. (2015) Pathways for irrigation development in Africa – insights from Ethiopia, Morocco and Mozambique, Working paper 119, Brighton: FAC.

Ongoma, V., Chen, H. and Goa, C. (2017) Projected changes in mean rainfall and temperature over East Africa based on CMIP5 models, International Journal of Climatology, Volume 38, Issue 3, pp 1375 -1392.

Osima, S., Indasi, V. S., Zaroug, M., Endris, H. E., Gudoshava, M., Misiani, H. O., Nimusiima, A., Anyah, R. O., Otieno, G., Ogwang, B.,A., Jain, S., Kondowe, A. L., Mwangi, E., Lennard, C., Nikulin, G. and Dosio, A. (2018) Projected climate over the Greater Horn of Africa under 1.5°C and 2°C global warming, Environ. Res. Lett. Volume 13

Paillard, S., Treyer, S., Bruno, D. (eds) (2011) Agrimonde: Scenarios and Challenges for feeding the world in 2050. Springer, Editions Quae, Versailles.

Parkes, B., Defrance, D., Sultan, B., Ciais, P. and Wang, X. (2018) Projected changes in crop yield mean and variability over West Africa in a world 1.5 K warmer than the pre-industrial era, Earth Syst. Dynam., Volume 9, pp 119-134.

Pavelic, P., Smakhtin, V., Favreau, G. and Villholth, K. G. (2012) Water balance approach for assessing potential for smallholder groundwater irrigation in Sub-Saharan Africa. Water SA, Volume 38, pp. 399-406.

Pavelic, P., Villholth, K. G., Shu, Y., Rebelo and L., Smakhtin, V. U. (2013) Smallholder groundwater irrigation in Sub-Saharan Africa: country-level estimates of development potential. Water International, Volume 38, pp. 392-407.

Peel, M. C., Finlayson, B. L., and McMahon, T. A. (2007) Updated world map of the Köppen-Geiger climate classification. Hydrology and Earth System Science, Volume 11, pp. 1633–1644.

Pieser, L. (2014) Senior Water Management Officer at FAO [Interview] (20 November 2014).

Pingali, P., Witner, M. and Abraham, M. (2016) Getting to zero hunger from the MDGs for the SDGs, In: International Society and sustainable Development Goals, Duran Y Lalaguna, P., Diaz Barrado, C. and Fernandez Lieza, C. (Eds), Aranzadi, Cizur Menor.

Pinstrup-Andersen, P. and Shimokawa, S. (2006) Rural Infrastructure and Agricultural Development. Paper prepared for presentation at the Annual Bank Conference on Development Economics, Tokyo, Japan, May 29-30, 2006.

Polack, P. (2004) Water and the other three revolutions needed to End Rural Poverty, Water Sciences and Technology, Volume 51, issue 8, pp. 134-143. Portmann, F. T., Siebert, S. and Döll1, P. (2010) MIRCA2000 – Global monthly irrigated and rainfed crop areas around the year 2000: A new high-resolution data set for agricultural and hydrological modelling. Global Biochem. Cy., Volume 24.

Pokhrel, Y., Hanasaki, N., Pat J-F. Yeh, P.J.F., Yamada, T. J., Kanae, S. and Oki, T. (2012) Nature Geoscience, Volume 5, pp 298-392.

Portmann, F. T., Siebert, S. and Döll1, P. (2010) MIRCA2000 – Global monthly irrigated and rainfed crop areas around the year 2000: A new high-resolution data set for agricultural and hydrological modelling, Global Biochem. Cy., 24, GB1011, doi:10.1029/2008GB003435.

Prihar, S., Arora, V. and Jalota, S. (2010) Enhancing crop water productivity to ameliorate groundwater decline. Current Science, Volume 99 (5), pp. 588-593.

Rahman, M. and Parvin, L. (2009) Impact of irrigation on food security in Bangladesh for the Past Three decades. J. Water Resource and Protection, Volume 3, pp. 216-225.

Ramankutty, N., Evan, A., Monfreda, C., and Foley, J. (2008) Farming the planet: 1. Geographic distribution of global agricultural lands in the year 2000. Global Biogeochem. Cy., Volume 22.

Riedel, C. and Döll, P. (2015) Global-scale modeling and quantification of indicators for assessing transboundary aquifers. In: GEF Transboundary Waters Assessment Programme (TWAP), Frankfurt.

Roudier, P., Ducharne, A. and Feyen L. (2014) Climate change impacts in runoff in West Africa: a review, Hydrol. Earth Syst. Sci., Volume 18, pp. 2789-2801.

Savenije, H. H. G. (2004) The importance of interception and why we should delete the term evapotranspiration from our vocabulary, Hydrol. Process., Volume 18, pp. 1507–1511.

Seguin JJ. and Gutierrez A. (2016) Les ressources en eau du continent africain :rareté et abondance, Géosciences, la revue du BRGM pour une Terre durable, Volume 21, pp. 58-66.

Shah, T. (2009) Taming the anarchy: groundwater governance in South Asia, Irrigation Science, Volume 28, Issue 3, pp 281-284.

Shah, T., Molden, D., Sakthivadivel, R. and Seckler, D. (2001) The global groundwater situation: opportunities and challenges. Economic and Political Weekly, Volume 36, Issue 43, pp 4142-4150.

Shah, T., Roy, A. D., Qureshi. Asad, S. and Wang, J. (2003) Sustaining Asia's Groundwater Boom. Natural Resources Forum, Volume 27, pp. 130-140.

Siebert, S. and Döll, P. (2010) Quantifying blue and green virtual water contents in global crop production as well as potential production losses without irrigation. Journal of Hydrology, Volume 384, pp. 198-217.

Siebert, S., Burke, J., Faures, J., Frenken, K., Hoogeveen, J., Döll, P. and Portmann, F. T. (2010) Groundwater use for irrigation - a global inventory. Hydrology and Earth System Sciences, Volume 14, pp. 1863-1880.

Siebert, S., Henrich, V., Frenken, K. and Burke, J. (2013) Global Map of Irrigation Areas version 5. Available at: http://www.fao.org/nr/water/aquastat/irrigationmap/index10.stm (last access: 28 march 2018).

Siebert, S., Kummu, M., Porkka, M., Döll P., Ramankutty, N. and Scanlon B. R. (2015) A global dataset of the extent of irrigated land from 1900 to 2005. Hydrology and Earth System Sciences, Volume 19, pp. 1521-2015.

Sood, A., Prathapar, S. A. and Smakhtin, V. (2014) Green and blue water. In: Lautze J. (Ed) Key concepts in water resource management: a review and critical evaluation, Routledge London and New York.

Sys, C., Van Ranst, E., Debaveye, J. and Beernaa, F. (1993) Land Evaluation – Parts I, II and III. General Administration for Development Cooperation, Brussels.

Taylor, R. G., Scanlon, B., Doll, P., Rodell, M., Van Beek, R., Wada, Y., Longuevergne, L., Leblanc, M., Famiglietti, J. S., Edmunds, M., Konikow, L., Green, T. R., Chen, J., Taniguchi, M., Bierkens, M. F., MacDonald, A., Fan, Y., Maxwell, R. M., Yechieli, Y., Gurdak, J., Allen, D. M., Shamsudduha, M., Hiscock, K., Yeh, P. J.-F., Holman, I., Treidel, H. (2013) Ground water and climate change, Nature Climate Change, Volume 3, pp 322-329.

Tomlinson, M. (2011) Ecological Water Requirements of Groundwater Systems: A Knowledge and Policy Review. Waterlines Report Series No. 68, National Water Commission, Canberra.

Turral, H., Burke, J., and Faurès, J.M. (2011) Climate change, water and food security, FAO Water Reports 36, FAO, Rome.

Tweed, S, Celle-Jeanton, H, Cabot L, Huneau, F, De Montety, V, Nicolau, N, Travi, Y, Babic, M, Aquilina, L, Vergnaud-Ayraud, V and Leblanc, M (2018) Impact of irrigated agriculture on groundwater resources in a temperate humid region, Sci Total Environ., Volume 613-614, pp 1302-1316.

UNECA and AfDB (2010) The African Water Vision for 2025: Equitable and Sustainable Use of Water for Socioeconomic Development. Economic Commission for Africa, Addis Ababa.

UNEP (1996) Groundwater: a threatened resource, UNEP Environment Library No 15, United Nations Environment Programme (UNEP), Nairobi.

UNEP (2008) Africa: Atlas of Our Changing Environment, Division of Early Warning and Assessment (DEWA), United Nations Environment Programme (UNEP), Nairobi.

United Nations (2015) The Millennium Development Goals report 2015. United Nations, New York.

USGS (2017) SRTM Water Body dataset. Available at https://lta.cr.usgs.gov/srtm_water_body_dataset (last access: 01 august 2018).

Van Beek, L. P. H., Wada, Y., and Bierkens, M. F. P. (2011) Global monthly water stress: I. Water balance and water availability. Water Resour. Res., Volume 47,

Verdin, K., Godt, J. W., Funk, C. C., Pedreros, D., Worstell, B. and Verdin, J. (2007) Development of a global slope dataset for estimation of landslide occurrence resulting from earthquakes. Open-File Report 2007-1188, U.S. Geological Survey, Colorado.

Villholth, G. K. (2013) Groundwater irrigation for smallholders in Sub-Sahara Africa - a synthesis of current knowledge to guide sustainable outcomes. Water international, Volume 38 (4), pp. 369-391.

Villholth, K.G., Sood, A., Liyanage, N., Zhu, T (unpublish) The role of groundwater and depleting aquifers in global irrigated food production.

Villholth, K. G., Ganeshamoorthy, J., Rundblad, C. M., Knudsen, T. S. (2013a) Smallholder groundwater irrigation in sub-Saharan Africa: an interdisciplinary framework applied to the Usangu plains, Tanzania, *Hydrogeology Journal*, Volume 21, pp. 1481-1495. Doi: 10.1007/s10040-013-1016-x.

Villholth, K. G., Tottrup, C., Stendel, M. and Maherry, A. (2013b) Integrated mapping of groundwater drought risk in the Southern African Development Community (SADC) Region. Hydrogeology Journal, Volume 21 (4), pp. 863-885.

Wada, Y., Van Beek, L, Van Kempen, C., Reckman, J. Vasak, S. and Bierkens, M. (2010) Global depletion of groundwater resources, Geophysical Research Letters, Volume 37.

Wada, Y., Van Beek, L, Viviroli, D., Dürr, H., Weingartner, R., and Bierkens, M. (2011) Global monthly water stress: 2. Water demand and severity of water stress. Water Resour. Res., Volume 47.

Wada, Y., Van Beek, and Bierkens, M. (2012) Nonsustainable groundwater sustaining irrigation: A global assessment, Water Resources Research, Volume 48, Issue 6.

Wale, A., Collick, A.S., Rossiter, D.G., Langan, S. and Steenhuis, T.S. (2013) Realistic assessment of irrigation potential in the Lake Tana basin, Ethiopia. In: Wolde. M. (ed), Rainwater management for resilient livelihoods in Ethiopia: Proceedings of the Nile Basin Development Challenge science meeting. NBDC Technical Report 5, International Livestock Research Institute, Nairobi.

Wazeda, S. M., Hughesa, B. R., O'Connora, D. and Calautitb, J. K. (2018) A review of sustainable solar irrigation systems for Sub-Saharan Africa. Renewable and Sustainable Energy Reviews, Issue 81, pp. 1206-1225.

Wheeler, T. and Von Braun, J. (2013) Climate Change Impacts on Global Food Security, Science, Volume 341, Issue 6145, pp. 508-513.

Wriedt, G., Velde, M., Aloe, A. and Bouraoui, F. (2009). Water requirement for irrigation in European Union, Joint Research Centre and Institute of Environment and Sustainability, Luxemburg.

Woodhouse, P, Veldwisch, G.J., Venot, J.P., Brockington, D., Komakech, H. and Manjichi, Â (2017) African farmer-led irrigation development: re-framing agricultural policy and investment?, The Journal of Peasant Studies, Volume 44, Issue No. 1, pp.213–233.

Worqlul, A., Jeong, J., Dile, Y. Y., Osorio, J., Schmitter, P., Gerik, T. Srinivasan, R. and Clark, N. (2017) Assessing potential land suitable for surface irrigation using groundwater in Ethiopia. Applied Geography, Volume 85, pp. 1-13.

Xie, H., You, L., Wielgosz, B. and Ringler, C. (2014) Estimating the potential for expanding smallholder irrigation. Agricultural Water Management, Volume 131, pp. 183-193.

You, L., Ringler, C., Wood-Sichra, U., Robertson, R., Wood, S., Zhu, T., Nelson, G., Guo, Z. and Sun, Y. (2011) What Is the Irrigation Potential for Africa? A Combined Biophysical and Socioeconomic Approach. IFPRI Discussion Paper 00993, June 2010.

Zhou, X. and Moinuddin, M. (2017) Sustainable Development Goals interlinkages and Network Analysis: a practical tool for SDG integration and policy coherence. Institute for Global Environmental Strategies (IGES), Kanagawa.

Zinyengere, N. and Crespo, O. (2017) Chapter 2 - Assessing Local Impacts of Climate Change on Crop Production in Southern Africa: Critiquing an Approach, In: Zinyengere, N., Theodory, T. F., Gebreyes, M. and Speranza, C. I. (eds) Beyond Agriculture Impact Multiple Perspectives on Climate Change and Agriculture in Africa, Academic Press, Elsevier, London.

Annexes

Annex 1: Calculation of the groundwater irrigation potential

This annex describes in details the computation method applied, including specific highlight on the green water data. The calculations are done for each of the 0.5°*0.5° grid cells using the following four equations:

$$GWIP = \frac{GW\ Available}{Irrig.\ Water\ Demand_{max}}\ [\mathrm{L}^2] \quad (1)$$

$$GW\ Available = GW\ Recharge - Human\ GW\ Demand - Environ.\ GW\ Req.\quad [\mathrm{L}^3\ \mathrm{T}^{-1}] \quad (2)$$

$$Irrig.Water\ Demand = \frac{Net\ Irrg.Water\ Demand}{Irrig.\ Efficiency}$$

$$= \frac{\{\sum_{i=1}^{n}\left(\left[\sum_{j=1}^{m}(Crop\ Water\ Demand - Green\ Water)_j\right] \times [\%\ of\ Area]_i\right)\}}{Irrig.\ Efficiency}\ [\mathrm{L\ T}^{-1}] \quad (3)$$

$$Crop\ Water\ Demand_j = Crop\ Group\ Coefficient \times E_{0,max_j}\ [\mathrm{L\ T}^{-1}] \quad (4)$$

Parameters of Eq. 2

GW Recharge is entered as annual values over the 41 years period (1960 – 2000). Annual values are calculated by summing monthly values directly extracted from the PCR-GLOBWB model.

Human GW Demand is calculated based on the map of population and livestock density from 2000 (FAO, 2007a, b) and data on unit daily water demand per capita (for domestic and industrial use) and per livestock type (Table 3.3, published article). The calculated data represent the annual aggregated water requirement for domestic, industrial and livestock for the year 2000.

Environ. GW Req. is a percentage of the annual *GW recharge*, applying three scenarios: the environmental groundwater requirements represent 70% (Scenario 1), 50% (Scenario 2), and 30% (Scenario 3) of the recharge, respectively. It is calculated for every year of the 41-year period.

GW available represents the annual groundwater surplus for GWI. It is calculated for every year of the 41-year period, then averaged over the 41 years.

Parameters of Eq. 3 and Eq. 4

Crop Water Demand is the monthly crop water demand for each crop group and is determined using Eq. 4.

$E_{0,maxj}$ is entered as the maximum of the monthly reference potential evapotranspiration over the 41-year period (1960 – 2000). The monthly E_0 values are directly extracted from the PCR-GLOBWB model.

The *Crop Group Coefficient* K_c is the monthly Crop Group Coefficient calculated using Table A1.1 – A1.4. Table A1.1 presents the monthly Crop Coefficient for each individual crop determined by disaggregating the seasonal *Crop Coefficient Kc* per growth period into monthly values using the length of the four common growth periods (initial, development, middle and late). Both seasonal K_c and growth periods are from the literature (FAO, 1986 and 1992).

Table A1.1: Seasonal and disaggregated monthly Crop Coefficient

Crop Group	Crop Type		K_c per Growth Period (mm)				Monthly Kc					
			Initial	Develop.	Middle	Late	1	2	3	4	5	6
Cereals	Maize	Period (days)	30	50	60	40	0.4	0.8	0.92	1.15	1.05	0.85
		Kc	0.4	0.8	1.15	0.85						
	Millet	Period (days)	20	30	55	35	0.35	0.77	1.1	0.97	0.58	
		Kc	0.35	0.7	1.1	0.7						
	Rice	Period (days)	30	30	80	40	1.05	1.1	1.2	1.2	1.05	0.75
		Kc	1.05	1.1	1.2	0.75						
	Sorghum	Period (days)	20	35	45	30	0.48	0.81	1.1	0.8	0.22	
		Kc	0.35	0.75	1.1	0.65						
	Wheat	Period (days)	15	30	65	40	0.53	0.9	1.1	0.83	0.3	
		Kc	0.35	0.7	1.1	0.3						
Oils	Groundnut	Period (days)	30	40	45	25	0.45	0.75	0.95	0.99	0.47	
		Kc	0.45	0.75	1.05	0.7						
	Soybean	Period (days)	20	30	70	30	0.48	0.87	1.1	1.1	0.6	
		Kc	0.35	0.75	1.1	0.6						
	Sunflower	Period (days)	25	35	45	25	0.42	0.75	1.15	0.85	0.18	
		Kc	0.35	0.75	1.15	0.55						
Roots	Potato	Period (days)	30	35	50	30	0.45	0.75	1.08	1.1	0.71	
		Kc	0.45	0.75	1.15	0.85						
Pulses	Bean	Period (days)	20	30	40	20	0.47	0.83	1.1	0.2		
		Kc	0.35	0.7	1.1	0.3						
	Lentil	Period (days)	25	35	70	40	0.5	0.75	1.1	1.1	0.7	0.33
		Kc	0.45	0.75	1.1	0.5						
Vegetables	Cucumber	Period (days)	25	35	50	20	0.49	0.7	0.9	0.85	0.25	
		Kc	0.45	0.7	0.9	0.75						
	Eggplant	Period (days)	30	40	45	25	0.45	0.75	1.02	1.09	0.53	
		Kc	0.45	0.75	1.15	0.8						
	Melon	Period (days)	30	45	65	20	0.45	0.75	0.88	1	0.92	0.25
		Kc	0.45	0.75	1	0.75						
	Onion	Period (days)	25	40	20	10	0.54	0.75	0.99	0.17		
		Kc	0.5	0.75	1.05	1						
	Pepper	Period (days)	30	40	40	20	0.35	0.7	0.93	1	0.3	
		Kc	0.35	0.7	1.05	0.9						
	Tomato	Period (days)	35	45	40	25	0.45	0.7	0.88	1.15	0.67	
		Kc	0.45	0.75	1.15	0.8						
Sugarcane	Sugarcane	Period (days)	35	70	180	80	0.4	0.9	1	1.13	1.25	1.25
		Kc	0.4	1	1.25	0.75	1.25	1.25	1.25	1	0.75	0.88

The *monthly Crop Coefficient* is calculated as follows:

$$monthly\ Crop\ Coefficient = \sum_{i=1}^{n}\left(Kc_{growth\ period_i} \times \frac{no\ days\ per\ month_{growth\ period_i}}{30}\right) \quad (5)$$

The case of tomato illustrates the calculation. Table A1.2 shows the growth period-based Kc values for tomato.

Table A1.2: Seasonal Crop Coefficient, Kc, and growth periods for tomato

	Growth periods (days)			
	initial	develop	middle	Late
Period (days)	35	45	40	25
Kc	0.45	0.75	1.15	0.8

Noting that the total cropping period for tomato is 145 days (approximately 5 months), the calculation of monthly Crop Coefficient is shown in Table A1.3.

Table A1.3: Calculation of monthly Crop Coefficient for tomato

Months	Monthly Crop Coefficient
Month 1	$K_c = \left(0.45 \times \frac{30}{30}\right) = 0.45$
Month 2	$K_c = \left(0.45 \times \frac{5}{30} + 0.75 \times \frac{25}{30}\right) = 0.7$
Month 3	$K_c = \left(0.75 \times \frac{20}{30} + 1.15 \times \frac{10}{30}\right) = 0.88$
Month 4	$K_c = \left(1.15 \times \frac{30}{30}\right) = 1.15$
Month 5	$K_c = \left(0.8 \times \frac{25}{30}\right) = 0.67$

Table A1.4 gives the crop calendar and the monthly *Crop Group Coefficient* for the 23 irrigation cropping pattern zones. The calendar indicates the cropping season of the crop groups for up to two cropping seasons per year (FAO crop calendar[26]; FAO, 1992 and FAO 1986). It also specifies the most prevalent (up to six individual) seasonal crops inventoried within each crop group of each irrigation cropping pattern zone (FAO crop calendar). The lumping of the crops has been done because these crops are similar in terms of season of cultivation. Because the crop coefficient of individual crops in a season and within a crop group may differ significantly, a conservative approach is applied, whereby the larger figure for the crops within a crop group have been applied, unless the difference between them is equal to or more than 0.05 and 0.1, in which case the larger coefficient is reduced by 0.01 or 0.02, respectively. The reason for applying the conservative approach is to ensure that the GWIP is not overestimated.

---

[26] http://www.fao.org/agriculture/seed/cropcalendar/welcome.do (last access: 31 March) 2014)

Table A1.4: Crop calendar and monthly Crop Group Coefficient for each crop group within the irrigation cropping pattern zones

Irrigation Cropping Pattern Zones	Crop Groups	Crop(s) in Crop Group (depending on season)	Crop Group Coefficient											
			Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	Cereals	Millet/Wheat	0.95	0.56								0.51	0.88	1.1
		Maize/Wheat				0.51	0.89	1.08	1.13	1.03	0.83			
	Oil	Groundnut/Sunflower	0.45	0.75	1.13	0.97	0.45							
		Soybean						0.48	0.87	1.1	1.1	0.6		
	Roots	Potatoes		0.45	0.75	1.08	1.1	0.71						
		Potatoes							0.45	0.75	1.08	1.1	0.71	
	Pulses	Bean/Lentil	1.1	1.08	0.68	0.31							0.5	0.82
		None												
	Vegetables	Eggplant/Pepper/Tomato					0.44	0.74	1	1.13	0.65			
		Eggplant/Pepper/Tomato	1	1.13	0.65								0.44	0.74
	Sugarcane	None												
2	Cereals	Millet/Wheat	1.1	0.95	0.56								0.51	0.88
		Maize/Rice/Wheat					1.03	1.08	1.18	1.18	1.03	0.83		
	Oil	Groundnut/Soybean/Sunflower	0.47	0.85	1.13	1.08	0.58							
		Groundnut/Sunflower						0.45	0.75	1.13	0.97	0.45		
	Roots	Potatoes			0.45	0.75	1.08	1.1	0.71					
		Potatoes	0.71								0.45	0.75	1.08	1.1
	Pulses	Bean/Lentil	1.08	0.68	0.31							0.5	0.82	1.1
		None												
	Vegetables	Cucumber/Melon/Tomato	1.13	0.9	0.23							0.49	0.74	0.9
		Cucumber/Melon/Pepper/Tomato				0.47	0.74	0.92	1.13	0.9	0.23			
	Sugarcane	None												
3	Cereals	Maize/Millet/Rice	1.03	1.08	1.18	1.18	1.03	0.83						
		Maize/Millet/Rice							1.03	1.08	1.18	1.18	1.03	0.83
	Oil	Groundnut/Soybean				0.48	0.85	1.08	1.08	0.58				
		Sunflower	0.18								0.42	0.75	1.15	0.85
	Roots	Potatoes					0.45	0.75	1.08	1.1	0.71			
		Potatoes	1.08	1.1	0.71								0.45	0.75
	Pulses	Lentil						0.5	0.75	1.1	1.1	0.7	0.33	
		None												
	Vegetables	Eggplant/Onion/Pepper/Tomato		0.52	0.74	1	1.13	0.65						
		Eggplant/Onion/Pepper/Tomato								0.52	0.74	1	1.13	0.65
	Sugarcane	Sugarcane	0.4	0.9	1	1.13	1.25	1.25	1.25	1.25	1.25	1	0.75	0.88
4	Cereals	Maize/Millet/Wheat		0.51	0.88	1.08	1.13	1.03	0.83					
		Maize/Millet/Wheat	0.83							0.51	0.88	1.08	1.13	1.03
	Oil	Groundnut/Soybean/Sunflower		0.47	0.85	1.13	1.08	0.58						
		Groundnut/Soybean/Sunflower	0.58								0.47	0.85	1.13	1.08

	Roots	Potatoes			0.45	0.75	1.08	1.1	0.71					
		Potatoes	1.1	0.71								0.45	0.75	1.08
	Pulses	Bean/Lentil			0.5	0.82	1.1	1.08	0.68	0.31				
		Bean/Lentil	0.68	0.31							0.5	0.82	1.1	1.08
	Vegetables	Eggplant/Pepper/Tomato	0.65								0.44	0.74	1	1.13
		Eggplant/Pepper/Tomato		0.44	0.74	1	1.13	0.65						
	Sugarcane	Sugarcane	0.4	0.9	1	1.13	1.25	1.25	1.25	1.25	1.25	1	0.75	0.88
5	Cereals	Maize/Rice/Wheat	1.08	1.18	1.18	1.03	0.83							1.03
		Maize/Millet/Rice						1.03	1.08	1.18	1.18	1.03	0.83	
	Oil	Groundnut		0.45	0.75	0.95	0.99	0.47						
		Groundnut							0.45	0.75	0.95	0.99	0.47	
	Roots	Potatoes	1.08	1.1	0.71								0.45	0.75
		Potatoes					0.45	0.75	1.08	1.1	0.71			
	Pulses	Bean						0.47	0.83	1.1	0.2			
		Bean	1.1	0.2									0.47	0.83
	Vegetables	Eggplant/Melon/Pepper/Tomato			0.44	0.74	1	1.13	0.9	0.23				
		Tomato	1.15	0.67								0.45	0.7	0.88
	Sugarcane	None												
6	Cereals	Maize/Rice			1.03	1.08	1.18	1.19	1.05	0.84				
		Maize	1.05	0.85							0.4	0.8	0.92	1.15
	Oil	Groundnut/Soybean				0.48	0.85	1.08	1.08	0.58				
		Groundnut/Soybean	0.58								0.48	0.85	1.08	1.08
	Roots	Potatoes					0.45	0.75	1.08	1.1	0.71			
		Potatoes	1.1	0.71								0.45	0.75	1.08
	Pulses	Bean				0.47	0.83	1.1	0.2					
		Bean	0.2									0.47	0.83	1.1
	Vegetables	Onion/Pepper/Tomato	1.13	0.65								0.52	0.74	0.97
		Cucumber/Eggplant/Pepper/Tomato				0.47	0.74	1	1.13	0.65				
	Sugarcane	Sugarcane	0.4	0.9	1	1.13	1.25	1.25	1.25	1.25	1.25	1	0.75	0.88
7	Cereals	Millet						0.35	0.77	1.1	0.97	0.58		
		Sorghum	1.1	0.8	0.22								0.48	0.81
	Oil	Groundnut							0.45	0.75	0.95	0.99	0.47	
		None												
	Roots	Potatoes				0.45	0.75	1.08	1.1	0.71				
		Potatoes	1.1	0.71								0.45	0.75	1.08
	Pulses	Lentil						0.5	0.75	1.1	1.1	0.7	0.33	
		None												
	Vegetables	Cucumber/Tomato	1.13	0.65								0.49	0.7	0.9
		Eggplant/Melon			0.45	0.75	1	1.08	0.9	0.23				
	Sugarcane	None												
8	Cereals	Maize/Rice				1.03	1.08	1.18	1.19	1.05	0.84			
		Maize/Rice	1.19	1.05	0.84							1.03	1.08	1.18

	Oil	Groundnut/Soybean			0.48	0.85	1.08	1.08	0.58					
		Groundnut/Soybean	1.08	0.58								0.48	0.85	1.08
	Roots	Potatoes		0.45	0.75	1.08	1.1	0.71						
		Potatoes								0.45	0.75	1.08	1.1	0.71
	Pulses	Bean	1.1	0.2									0.47	0.83
		Bean					0.47	0.83	1.1	0.2				
	Vegetables	Cucumber/Melon/Onion/Tomato		0.53	0.74	0.97	1.13	0.9	0.23					
		Cucumber/Melon/Onion/Tomato	0.23							0.53	0.74	0.97	1.13	0.9
	Sugarcane	None												
9	Cereals	Maize/Rice	1.18	1.19	1.05	0.84							1.03	1.08
		Wheat					0.53	0.9	1.1	0.83	0.3			
	Oil	Groundnut/Soybean	0.48	0.85	1.08	1.08	0.58							
		Groundnut/Soybean						0.48	0.85	1.08	1.08	0.58		
	Roots	Potatoes			0.45	0.75	1.08	1.1	0.71					
		Potatoes	1.1	0.71								0.45	0.75	1.08
	Pulses	Bean				0.47	0.83	1.1	0.2					
		Bean	1.1	0.2									0.47	0.83
	Vegetables	Onion/Tomato		0.53	0.74	0.97	1.13	0.65						
		Onion/Tomato								0.53	0.74	0.97	1.13	0.65
	Sugarcane	None												
10	Cereals	Maize/Rice/Sorghum					1.03	1.08	1.18	1.18	1.03	0.83		
		Rice/Sorghum/Wheat	1.19	1.18	1.03	0.73							1.03	1.08
	Oil	Groundnut					0.45	0.75	0.95	0.99	0.47			
		Groundnut/Soybean/Sunflower	1.08	0.58								0.47	0.85	1.13
	Roots	Potatoes		0.45	0.75	1.08	1.1	0.71						
		Potatoes	0.71								0.45	0.75	1.08	1.1
	Pulses	Lentil	1.1	0.7	0.33							0.5	0.75	1.1
		Bean				0.47	0.83	1.1	0.2					
	Vegetables	Melon/Onion/Tomato	0.9	0.23							0.53	0.74	0.97	1.13
		Melon/Onion/Pepper/Tomato			0.52	0.74	0.97	1.13	0.9	0.23				
	Sugarcane	None												
11	Cereals	Maize/Sorghum/Wheat				0.51	0.89	1.08	1.13	1.03	0.83			
		Maize/Rice/Sorghum	1.18	1.03	0.83							1.03	1.08	1.18
	Oil	Groundnut/Soybean/Sunflower					0.47	0.85	1.13	1.08	0.58			
		Groundnut/Soybean/Sunflower	1.13	1.08	0.58								0.47	0.85
	Roots	Potatoes				0.45	0.75	1.08	1.1	0.71				
		Potatoes	1.1	0.71								0.45	0.75	1.08
	Pulses	Bean/Lentil			0.5	0.82	1.1	1.08	0.68	0.31				
		Bean/Lentil	0.68	0.31							0.5	0.82	1.1	1.08
	Vegetables	Cucumber/Melon/Onion/Pepper/Tomato	0.52	0.74	0.97	1.13	0.93	0.23						
		Eggplant/Melon/Onion/Pepper/Tomato							0.52	0.74	1	1.13	0.9	0.23
	Sugarcane	Sugarcane	0.4	0.9	1	1.13	1.25	1.25	1.25	1.25	1.25	1	0.75	0.88

12	Cereals	Wheat					0.46	0.81	1.08	1.13	1.03	0.83		
		Maize/Millet/Sorghum	1.1	0.83	0.3								0.53	0.9
	Oil	Groundnut						0.45	0.75	0.95	0.99	0.47		
		None												
	Roots	Potatoes	1.08	1.1	0.71								0.45	0.75
		Potatoes				0.45	0.75	1.08	1.1	0.71				
	Pulses	Bean/Lentil	0.68	0.31							0.5	0.82	1.1	1.08
		Bean					0.47	0.83	1.1	0.2				
	Vegetables	Cucumber/Eggplant/Tomato		0.49	0.74	1	1.13	0.65						
		Cucumber/Melon/Onion/Pepper	0.23							0.52	0.74	1	1.13	0.9
	Sugarcane	None												
13	Cereals	Maize/Rice/Sorghum					1.03	1.08	1.18	1.18	1.03	0.83		
		Rice/Sorghum	1.19	1.18	1.03	0.73							1.03	1.08
	Oil	Sunflower	0.85	0.18								0.42	0.75	1.15
		Sunflower				0.42	0.75	1.15	0.85	0.18				
	Roots	Potatoes	1.1	0.71								0.45	0.75	1.08
		Potatoes				0.45	0.75	1.08	1.1	0.71				
	Pulses	Bean				0.47	0.83	1.1	0.2					
		Bean								0.47	0.83	1.1	0.2	
	Vegetables	Eggplant/Onion/Pepper/Tomato				0.52	0.74	1	1.13	0.65				
		Onion/Pepper/Tomato	1.13	0.65								0.52	0.74	0.97
	Sugarcane	None												
14	Cereals	Maize/Rice	1.19	1.05	0.84							1.03	1.08	1.18
		Maize/Millet/Rice/Sorghum				1.03	1.08	1.18	1.18	1.03	0.83			
	Oil	Groundnut/Soybean/Sunflower			0.47	0.85	1.13	1.08	0.58					
		Groundnut/Soybean/Sunflower	0.58								0.47	0.85	1.13	1.08
	Roots	Potatoes	0.71								0.45	0.75	1.08	1.1
		Potatoes		0.45	0.75	1.08	1.1	0.71						
	Pulses	Bean	0.2									0.47	0.83	1.1
		Bean			0.47	0.83	1.1	0.2						
	Vegetables	Eggplant/Onion/Pepper/Tomato				0.52	0.74	1	1.13	0.65				
		Eggplant/Onion/Pepper/Tomato	1.13	0.65								0.52	0.74	1
	Sugarcane	None												
15	Cereals	Maize/Rice/Sorghum				1.03	1.08	1.18	1.18	1.03	0.83			
		Maize/Rice/Sorghum	1.18	1.03	0.83							1.03	1.08	1.18
	Oil	Groundnut/Soybean/Sunflower	0.58								0.47	0.85	1.13	1.08
		Groundnut/Soybean/Sunflower			0.47	0.85	1.13	1.08	0.58					
	Roots	Potatoes			0.45	0.75	1.08	1.1	0.71					
		Potatoes	0.71								0.45	0.75	1.08	1.1
	Pulses	Bean	0.2									0.47	0.83	1.1
		Bean			0.47	0.83	1.1	0.2						

	Vegetables	Cucumber/Eggplant/Onion/Tomato			0.53	0.74	1	1.13	0.65					
		Eggplant/Onion/Tomato								0.52	0.74	1	1.13	0.65
	Sugarcane	Sugarcane	0.4	0.9	1	1.13	1.25	1.25	1.25	1.25	1.25	1	0.75	0.88
16	Cereals	Maize/Millet/Rice/Wheat	1.18	1.03	0.83							1.03	1.08	1.18
		Maize/Millet/Rice/Wheat				1.03	1.08	1.18	1.18	1.03	0.83			
	Oil	Groundnut/Soybean/Sunflower			0.47	0.85	1.13	1.08	0.58					
		Groundnut/Soybean/Sunflower	1.08	0.58								0.47	0.85	1.13
	Roots	Potatoes			0.45	0.75	1.08	1.1	0.71					
		Potatoes	1.1	0.71								0.45	0.75	1.08
	Pulses	Bean	0.2									0.47	0.83	1.1
		Bean			0.47	0.83	1.1	0.2						
	Vegetables	Cucumber/Eggplant/Melon/Onion/Pepper/Tomato		0.52	0.74	1	1.13	0.9	0.23					
		Cucumber/Eggplant/Melon/Onion/Pepper/Tomato	0.23							0.52	0.74	1	1.13	0.9
	Sugarcane	Sugarcane	0.4	0.9	1	1.13	1.25	1.25	1.25	1.25	1.25	1	0.75	0.88
17	Cereals	Maize/Millet/Rice/Sorghum/Wheat					1.03	1.08	1.18	1.18	1.03	0.83		
		Maize/Millet/Rice/Sorghum/Wheat	1.18	1.18	1.03	0.83							1.03	1.08
	Oil	Groundnut/Soybean/Sunflower			0.47	0.85	1.13	1.08	0.58					
		Groundnut/Soybean/Sunflower								0.47	0.85	1.13	1.08	0.58
	Roots	Potatoes				0.45	0.75	1.08	1.1	0.71				
		Potatoes	1.1	0.71								0.45	0.75	1.08
	Pulses	Bean				0.47	0.83	1.1	0.2					
		Bean	0.2									0.47	0.83	1.1
	Vegetables	Cucumber/Eggplant/Melon/Onion/Pepper/Tomato				0.52	0.74	1	1.13	0.9	0.23			
		Cucumber/Eggplant/Melon/Onion/Pepper/Tomato	1.13	0.9	0.23							0.52	0.74	1
	Sugarcane	Sugarcane	0.4	0.9	1	1.13	1.25	1.25	1.25	1.25	1.25	1	0.75	0.88
18	Cereals	Maize/Millet/Rice/Wheat				1.03	1.08	1.18	1.18	1.03	0.83			
		Maize/Rice/Sorghum/Wheat	1.18	1.03	0.83							1.03	1.08	1.18
	Oil	Groundnut/Soybean			0.48	0.85	1.08	1.08	0.58					
		Groundnut/Soybean	1.08	0.58								0.48	0.85	1.08
	Roots	Potatoes			0.45	0.75	1.08	1.1	0.71					
		Potatoes	1.1	0.71								0.45	0.75	1.08
	Pulses	Bean				0.47	0.83	1.1	0.2					
		Bean	0.2									0.47	0.83	1.1
	Vegetables	Cucumber/Eggplant/Melon/Onion/Pepper/Tomato			0.52	0.74	1	1.13	0.9	0.23				
		Cucumber/Eggplant/Melon/Onion/Pepper/Tomato	0.9	0.23							0.52	0.74	1	1.13
	Sugarcane	Sugarcane	0.4	0.9	1	1.13	1.25	1.25	1.25	1.25	1.25	1	0.75	0.88
19	Cereals	Maize	1.15	1.05	0.85							0.4	0.8	0.92
		Millet/Sorghum/Wheat				0.51	0.88	1.1	0.95	0.56				
	Oil	Groundnut/Sunflower	0.45	0.75	1.13	0.97	0.45							
		Groundnut/Sunflower						0.45	0.75	1.13	0.97	0.45		
	Roots	Potatoes	0.45	0.75	1.08	1.1	0.71							

		Potatoes						0.45	0.75	1.08	1.1	0.71		
	Pulses	Bean		0.47	0.83	1.1	0.2							
		None												
	Vegetables	Melon/Onion/Tomato		0.53	0.74	0.97	1.13	0.9	0.23					
		Melon	0.25							0.45	0.75	0.88	1	0.92
	Sugarcane	None												
20	Cereals	Millet/Rice/Sorghum	1.19	1.18	1.03	0.73							1.03	1.08
		Maize/Wheat					0.51	0.89	1.08	1.13	1.03	0.83		
	Oil	Groundnut/Soybean/Sunflower	0.85	1.13	1.08	0.58								0.47
		Groundnut/Soybean					0.48	0.85	1.08	1.08	0.58			
	Roots	Potatoes	1.08	1.1	0.71								0.45	0.75
		Potatoes				0.45	0.75	1.08	1.1	0.71				
	Pulses	Bean	0.47	0.83	1.1	0.2								
		None												
	Vegetables	Cucumber/Eggplant/Melon/Onion/Tomato			0.53	0.74	1	1.13	0.9	0.23				
		Eggplant/Onion/Tomato	0.65								0.52	0.74	1	1.13
	Sugarcane	Sugarcane	0.4	0.9	1	1.13	1.25	1.25	1.25	1.25	1.25	1	0.75	0.88
21	Cereals	Millet/Sorghum/Wheat					0.51	0.88	1.1	0.95	0.56			
		Maize/Millet/Sorghum/Wheat	1.08	1.13	1.03	0.83							0.51	0.88
	Oil	Groundnut/Soybean/Sunflower	0.85	1.13	1.08	0.58								0.47
		None												
	Roots	Potatoes				0.45	0.75	1.08	1.1	0.71				
		Potatoes	1.08	1.1	0.71								0.45	0.75
	Pulses	Bean	1.1	0.2									0.47	0.83
		Bean			0.47	0.83	1.1	0.2						
	Vegetables	Cucumber/Eggplant/Onion/Pepper/Tomato		0.52	0.74	1	1.13	0.65						
		Eggplant/Onion/Pepper/Tomato							0.52	0.74	1	1.13	0.65	
	Sugarcane	Sugarcane	0.4	0.9	1	1.13	1.25	1.25	1.25	1.25	1.25	1	0.75	0.88
22	Cereals	Maize/Millet/Sorghum/Wheat				0.51	0.88	1.08	1.13	1.03	0.83			
		Maize/Millet/Sorghum/Wheat	1.13	1.03	0.83							0.51	0.88	1.08
	Oil	Groundnut/Sunflower	0.75	1.13	0.97	0.45								0.45
		None												
	Roots	Potatoes	0.71								0.45	0.75	1.08	1.1
		Potatoes		0.45	0.75	1.08	1.1	0.71						
	Pulses	Bean		0.47	0.83	1.1	0.2							
		Bean							0.47	0.83	1.1	0.2		
	Vegetables	Onion/Pepper/Tomato			0.52	0.74	0.97	1.13	0.65					
		Pepper/Tomato	0.65								0.44	0.7	0.92	1.13
	Sugarcane	Sugarcane	0.4	0.9	1	1.13	1.25	1.25	1.25	1.25	1.25	1	0.75	0.88
23	Cereals	Maize	1.15	1.05	0.85							0.4	0.8	0.92
		Sorghum					0.48	0.81	1.1	0.8	0.22			

	Oil	None												
		None												
	Roots	Potatoes	0.45	0.75	1.08	1.1	0.71							
		Potatoes						0.45	0.75	1.08	1.1	0.71		
	Pulses	None												
		None												
	Vegetables	Cucumber/Onion/Pepper/Tomato			0.52	0.74	0.97	1.13	0.65					
		None												
	Sugarcane	Sugarcane	0.4	0.9	1	1.13	1.25	1.25	1.25	1.25	1.25	1	0.75	0.88

% of Area in Eq. 3 is the percentage of crop group area relative to total crop group area. It is taken from data for the 2000 crop distribution at 5 min resolution used by Monfreda et al. (2008) and Ramunkutty et al. (2008). The data have been rescaled at 0.5° resolution. The percentage is assumed constant for every month over the 41-year period.

Green Water corresponds to the water that plants can access from rainfall through soil moisture. The monthly values over the 41-year period are directly extracted from the PCR-GLOBWB global hydrological model and constitute the sum of the simulated actual transpiration of natural vegetation and rainfed crops from the first and second soil layer of the model (Wada et al., 2011). This definition can be contested as green water is sometimes expressed as the actual evapotranspiration. Falkenmark and Rockström (2006) distinguish two components of green water: the productive part, i.e. transpiration, involved in biomass production, and the non-productive part, i.e. soil evaporation. As opposed to Schuol et al. (2008), who consider that evaporation has potential to be partly used as productive green water for food production, a conservative approach is applied in this study to ensure that the GWIP is not overestimated, hence considering transpiration as the only water available from precipitation for crop growth. Figure A1.1 presents the distribution of average annual rainfall and green water over Africa as used in the calculations, as well as the ratio of green water to rainfall. The equatorial regions, except east Africa, have higher precipitation and higher absolute green water availability than the rest of Africa. However, the green water availability is not strictly proportional to the rainfall as the ratio of green water to rainfall decreases to less than 40% in tropical areas where evaporation is the main factor of water losses.

Net Irrig. Water Demand is calculated for each month over the 41-year period for the six (n=6) crop groups (cereals, oil crops, roots, pulses, vegetables and sugar crops), taking into account available green water and share of crop groups of total crop group area. The monthly values are summed per year, and then over the six crop groups.

Irrig. Efficiency is the irrigation efficiency coefficient (FAO, 1989). It is used to express the fraction of abstracted groundwater not lost along the water transport from the abstraction point to the crop. These distributed values (FAO, 1997) are assumed constant.

Irrig Water Demand (gross) is calculated from Net Irrig. Water Demand divided by the constant Irrig. Efficiency)

Parameters of Eq.1

GWIP is the groundwater irrigation potential, expressed in terms of area irrigable by the available groundwater and considering the gross irrigation water demand. It is calculated using average annual value for groundwater availability to account for the buffering effect of groundwater storage and using the maximum annual gross irrigation water demand over the 41year period, yielding one value per cell.

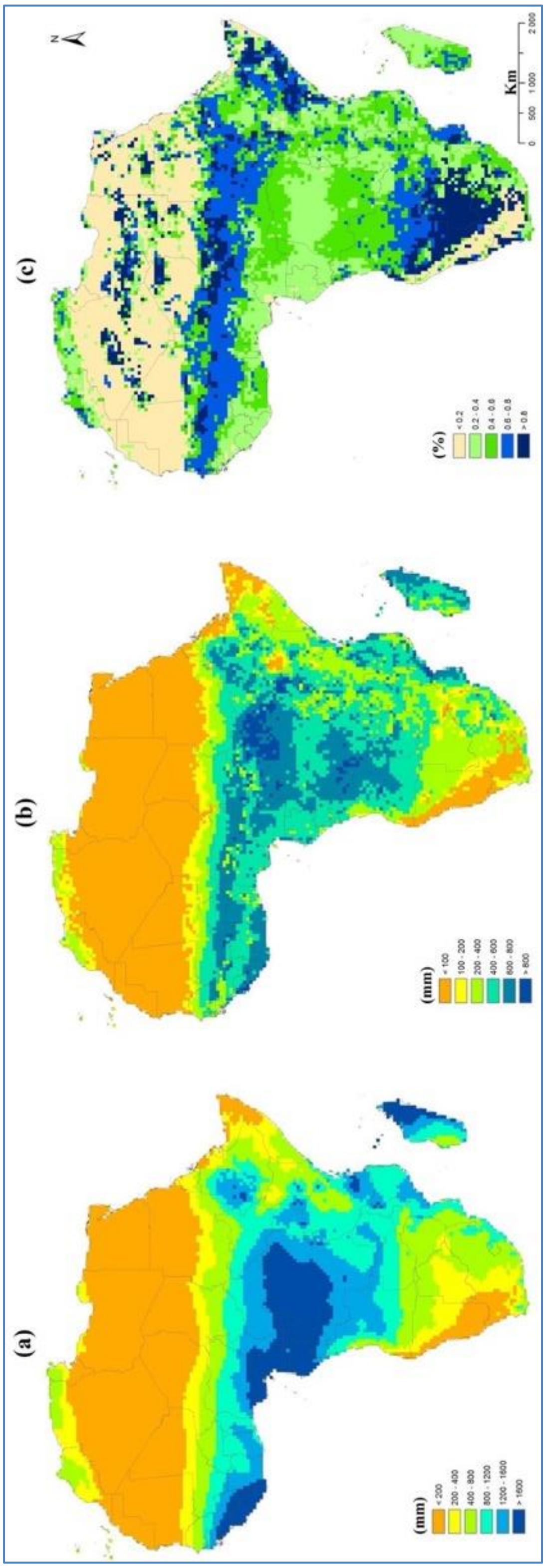


Figure A1.1. Average of (a) the annual rainfall and (b) the annual green water and (c) ratio of annual green water to rainfall, all given as averages over the 41-year period (1960-2000).

References

Falkenmark M. and Rockström J. (2006) The new blue and green water paradigm: Breaking new ground for water resources planning and management, J. Water Resour. Plann. Manage., 132 (3), 129– 132, 4 pp.

FAO (1986) Irrigation Water Management: Irrigation Water Need, Training Manual no. 3, edited by: Brouwer, C. and Heibloem, M., Food and Agriculture Organization of United Nations, Rome, Italy, 102 pp.

FAO (1989) Irrigation Water Management: Irrigation Scheduling, Training Manual no. 4, edited by: Brouwer, C., Prins, K., and Heibloem, M., Food and Agriculture Organization of United Nations, Rome, Italy, Land and Water Development Division, 66 pp.

FAO (1992) Crop Water Requirements, FAO Irrigation and Drainage Paper no. 24, edited by: Doorenbos, J., Pruitt, 5 W. O., Aboukhaled, A., Damagnez, J., Dastane, N. G., Van den Berg, C., Rijtema, P. E., Ashford, O. M., and Frere, M., Food and Agriculture Organization of United Nations, Land and Water Development Division, Rome, Italy, 144 pp.

FAO (1997) Irrigation Potential in Africa: A Basin Approach, FAO Land and Water Bulletin 4, Food and Agriculture Organization of United Nations, Land and Water Development Division, Rome, Italy, 177 pp.

FAO (2007a) Population density (persons/km2), available at: http://www.fao.org/geonetwork/srv/15en/resources.get?id=30586&fname=poprecl_ASCII.zip&access=private (last access:31 March 2014).

FAO (2007b) Gridded livestock of the world, available at: http://www.fao.org/ag/againfo/resources/en/glw/GLW_dens.html (last access: 31 March 2014).

Monfreda, C., Ramankutty N., and Foley J. A. (2008) Farming the planet: 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000, Global Biogeochem. Cy., 22, GB1022, doi:10.1029/2007GB002947.

Ramankutty N., Evan A., Monfreda C., and Foley J. (2008) Farming the planet: 1. Geographic distribution of global agricultural lands in the year 2000, Global Biogeochem. Cy., 22, GB1003, doi:10.1029/2007GB002952.

Savenije, H. H. G. (2004) The importance of interception and why we should delete the term evapotranspiration from our vocabulary, Hydrol. Processes, 18, 1507– 1511, 5 pp.

Schuol J., Abbaspour K. C., Yang H., Srinivasan R. and Zehnder A. J. B. (2008) Modelling blue and green water availability in Africa, Water Resour. Res., 44, W07406, doi:10.1029/2007WR006609.

Wada Y., Van Beek L, Viviroli D. Dürr H., Weingartner R. and Bierkens M. (2011) Global monthly water stress: 2. Water demand and severity of water stress, Water Resour. Res., 47, W07517, doi:10.1029/2010WR009792.

Annex 2: Mapping sustainable groundwater irrigation development driver (GIDD)

This annex proposed a detailed methodology for the construction of the GIDD which locates and ranks into conduciveness classes at a grid scale of 0.005-degree (about 0.5 x 0.5 km cell) the areas in Africa where it could be possible to develop sustainable groundwater irrigation. It also presents the intermediate results of the methodology. The method initially maps GIDD at a 0.005-degree resolution (0.5 x 0.5 km cell) with a combination of factors that would limit further groundwater irrigation if a physical resource potential was present: (i) it identifies the driving factors (e.g., access to surface water) that constrain or are conducive to further groundwater irrigation development, with each factor dependent upon one or more parameters; (ii) it builds continent-wide distributed maps of each parameter; (iii) it builds continent-wide distributed maps of each factor by combining the parameter maps when necessary and; (iv) it combines the maps of the individual driving factors of GIDD through a composite mapping analysis in GIS.

Selected driving factors

The selected driving factors to Groundwater Irrigation (GWI) development and the source of their datasets are described in Table A.2.1. Access to surface water (C) and access to market (D) depend on three parameters. The other driving factors depend on one parameter.

Table A2.1: Data sources of the selected driving factors.

Driving factors	Parameters	Initial dataset source	Resolution when applicable (degree)
A. Groundwater availability	Area irrigable with renewable groundwater	Altchenko and Villholth (2015) (http://waterdata.iwmi.org/pages/data_search.php?search_term=groundwater)	0.5°
B. Crop water need	Crop water need		
C. Access to surface water	Distance to perennial river	African river (http://www.fao.org/geonetwork/srv/en/metadata.show?id=37333	
	Distance to intermittent river		
	Distance to water bodies	Radar Topography Mission (SRTM - WBD) Water Body Data	
D. Access to market	Distance to small town extent (< 50000 inhabitants)	Global Rural-Urban Mapping Project (GRUMP) dataset (Balk et al., 2006 Urban extents ((http://dx.doi.org/10.7927/H4GH9FVG)) Settlement point ((http://dx.doi.org/10.7927/H4M906KR)	0.08333333°
	Distance to large town extent (> 50000 inhabitants)		
	Distance to road network	gROADS (http://dx.doi.org/10.7927/H4VD6WCT	
E. Terrain suitability for agriculture	Soil suitability index for agriculture with high inputs	Global Agro-ecological Zones (GAEZ) V.3 (http://gaez.fao.org/Main.html#)	0.08333333°
F. Borehole investment	Depth to water table	NERC – GWGW / BGS (http://www.bgs.ac.uk/research/groundwater/international/africangroundwater/requestMap.cfm)	0.05°

Mapping of individual GIDD for groundwater availability ($GIDD_A$)

For the driving factors of groundwater availability (A), the initial dataset is rescaled at a 0.005-degree resolution and cells with a value superior to 0 are extracted to create the individual GIDD maps ($GIDD_A$). Result is shown in Figure A2.1. $GIDD_A$ is strongly affected by climate patterns as arid areas with no sufficient renewable groundwater available for irrigation are obviously not conducive to GWI development.

Mapping of individual GIDD for crop irrigation need ($GIDD_B$)

For the driving factors of crop water need (B), the initial dataset is rescaled at a 0.005-degree resolution and cells with a value superior to 500 mm per year for crop water need (B) are extracted to create the individual GIDD maps ($GIDD_B$). Result is shown in Figure A2.1. $GIDD_B$ is strongly affected by climate patterns as equatorial areas with low crop water need are obviously not conducive to GWI development.

Only cells combining both threshold values for groundwater availability and crop irrigation need will be considered for the other individual GIDD maps. This means that their $GIDD_A$ and $GIDD_B$ are used as masks when the other individual GIDD maps are built. On the maps, this is translated by the location of the results along two visible corridors: a west-east stripe going from Senegal and Guinea to Ethiopia and a sizable north-south stripe along the Eastern part of Africa from Ethiopia to Angola and Zimbabwe. Arid and semi-arid areas (i.e., Sahara and Namib deserts, Kalahari and Eastern part of the Horn of Africa) and equatorial areas (i.e., South-western part of the West Africa coast and most of Gabon, Republic of Congo and Democratic Republic of the Congo) are quasi-excluded (no colour) from sustainable groundwater irrigation development.

Mapping of individual GIDD for access to surface water ($GIDD_C$)

The driving factors of access to surface water (C) depends on three parameters: distance to perennial rivers, distance to intermittent river and distance to water bodies. Each parameter is associated with a continental dataset features (line for rivers and polygon for water bodies). The process is based on a country assessment to take into consideration that there are no international exchanges or transfers between nations (i.e., no international water transfers). Under this process, he features are first clipped for each country to build a country dataset. Second, the features are converted into country rasters at 0.005-degree showing the distance to the closest feature within each country using the Euclidian distance tool in ArcGIS. Third, the nation rasters are aggregated to build the continental raster for each parameter which shows the distance to the closest feature (distance to perennial rivers, distance to intermittent river and distance to water bodies). The distances are binned into five classes of the level of conduciveness to GWI development (1=extremely conducive, 2=highly conducive, 3=moderately c conducive, 4=slightly conducive and 5= non-conducive), ranked from the most favourable class for groundwater irrigation development to the least favourable (thesis, Table 5). Finally, the analysis combines the parameters into individual driving factor maps ($GIDD_C$) by extracting the lowest level of conduciveness of each cell to be conservative with the approach. For example, as it relates to access to surface water, this means that if the class of conduciveness is 5 (not conducive) because the area is in the vicinity of a lake, the extracted class of conduciveness is 5 even if the classes of conduciveness of the other parameters are lower.

The ranking is derived from literature (Droogers et al., 2012; Wale et al., 2013; Worqlul et al., 2017), experience, and common sense. The ranking of access to surface water (A) reflects two considerations; since the surface water is easier to use than groundwater, it is assumed that proximity to surface water limits the use of groundwater for irrigation. As a result, the conduciveness exerted by the distance to surface water on groundwater irrigation development constraints (GIDD) is less significant when this distance is small and even more so if the surface water is perennial. However, it is assumed that there is extreme conduciveness near intermittent rivers since boreholes are often located in the associated alluvial groundwater zone.

Results are shown in Figure A.2.1. The map of $GIDD_A$ shows that inadequate access to surface water is a moderate conduciveness (green) for developing groundwater irrigation in the semi-arid regions of Africa. These regions include the Sahel, the Eastern Horn and the South-West part of Southern Africa, where intermittent rivers are frequent. In the other areas, moderate to high conduciveness (green and light blue) is found in between rivers.

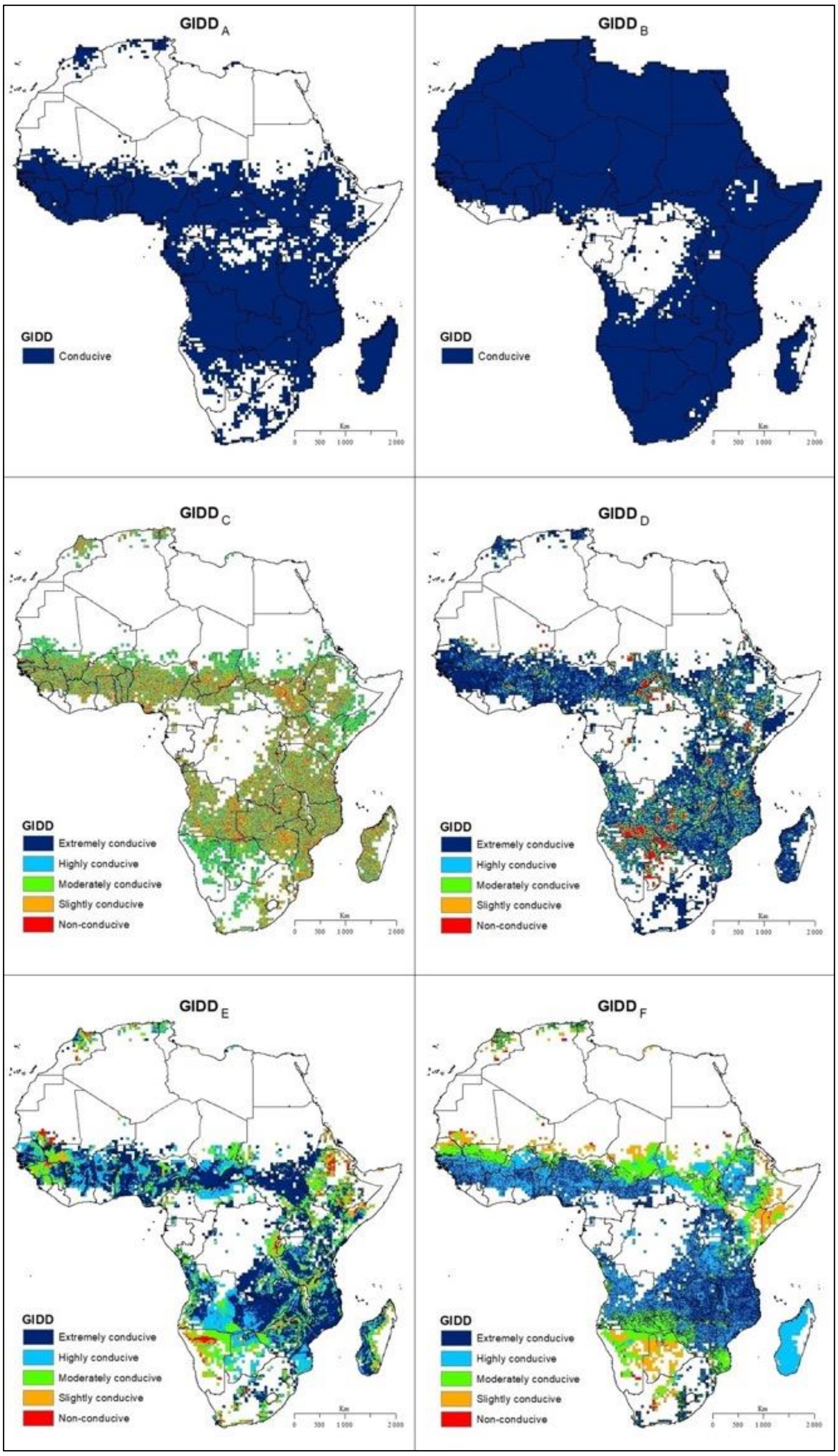


Figure A2.1: Individual groundwater irrigation development constraint from groundwater availability (GIDD$_{A}$), crop water need (GIDD$_{B}$), the access to surface water (GIDD$_{C}$), the access to market (GIDD$_{D}$), the terrain suitability for agriculture (GIDD$_{E}$), and the borehole investment (GIDD$_{F}$).

Mapping of individual GIDD for access to market ($GIDD_D$)

The driving factors of access to access to market (C) depends on three parameters: distance to small town (< 50 000 inhabitants), distance to big town (> 50 000 inhabitants) and distance to roads. Each parameter is associated with a continental dataset features (line for roads and polygon for town extent). The process is based on a country assessment to take into consideration that there are no international exchanges or transfers between nations (i.e., no international food trade). Under this process, the features are first clipped for each country to build a country dataset. Second, the features are converted into country rasters at 0.005-degree showing the distance to the closest feature within each country using the Euclidian distance tool in ArcGIS. Third, the nation rasters are aggregated to build the continental raster for each parameter which shows the distance to the closest feature (distance to small town, distance to big town and distance to roads). The distances are binned into five classes of the level of conduciveness to GWI development (1=extremely conducive, 2=highly conducive, 3=moderately c conducive, 4=slightly conducive and 5= non-conducive), ranked from the most favourable class for groundwater irrigation development to the least favourable (thesis, Table 5). Finally, the analysis combines the parameters into individual driving factor maps ($GIDD_D$) by extracting the lowest level of conduciveness of each cell to be conservative with the approach. The ranking is derived from literature (Droogers et al., 2012; Wale et al., 2013; Worqlul et al., 2017), experience, and common sense. The ranking of conduciveness exerted by the access to market (B) reflects that the conduciveness is higher closer to a city or road.

Results are shown in Figure A.2.1. The $GIDD_D$ presents mainly high (light blue) and extreme conduciveness (dark blue). In contrast, slightly conducive (orange) and non-conducive (red) are found in pockets corresponding to regions with low population and road density exhibit such as semi-arid area (e.g., Kalahari), tropical forest (i.e., Cameroon) or natural reserve (e.g., Okavango).

Mapping of individual GIDD for terrain suitability ($GIDD_E$)

For the driving factors of terrain suitability for agriculture (E), the initial dataset is already arranged into classes. The process rescales the dataset and bins the existing classes into the five classes of conduciveness (thesis, table 5). The conduciveness exerted by the index of soil suitability for agriculture (C) stems from the aggregation of existing classes of the soil suitability index.

Result is shown in Figure A2.1. The $GIDD_E$ map present mainly extremely and highly conducive areas (dark and light blue), including some part of Sahel. Slight and no conduciveness (orange and red) is essentially located in arid regions where sand dune can be found (i.e., Horn of Africa and Namibian desert) and in West Africa at the edge of Sahara Desert.

Mapping of individual GIDD for borehole investment ($GIDD_F$)

For the driving factors of borehole investment (F), the initial dataset is already arranged into classes. The process rescales the dataset and bins the existing classes into the five classes of conduciveness (thesis, table 5). The conduciveness exerted by borehole investment (D) mirrors the increase in cost associated with the depth of the borehole.

Result is shown in Figure A2.1. The $GIDD_F$ map is closely tied to climate since groundwater in the arid/semi-arid regions generally comes from fossil water and deep aquifers. Thus, the class of conduciveness is reducing from extremely to slightly conductive following the axis from equatorial areas to arid region $GIDD_D$. Then, slightly conducive areas are found in the Horn of East Africa, the Kalahari/Namibian desert regions and the north of Sahel.

Mapping of GIDD

The analysis combines the maps of the individual driving factors ($GIDD_C$, $GIDD_D$, $GIDD_E$ and $GIDD_F$) into the GIDD map through a composite mapping analysis in GIS first, using different weighting methods to determine the irrigation development obstacles per cell and second, extracting per cell the lowest level of conduciveness from the results of the various weighting methods to avoid overestimating the areas favourable to GWI development. Table A2.2 shows the different sets of weights applied to the individual GIDDs, which are the equal-weight method for each factor and four alternative weight sets, as proposed by Malczewski (1999) for use in GIS multi-criteria analysis. The equal-weight method (W1) assumes that all the factors have the same influence, while the other methods rank the relative influence of the various factors. The ranking sum (W2) and ranking reciprocal (W3) rank the factors while the pairwise comparison method (W4) and rating method (W5) rank the factors against each other and apply a rating, respectively. Hierarchizing and rating have been performed with common sense and expertise. Later, cells, where no groundwater irrigation is possible, are removed from the GIDD; this corresponds to the areas where inside water bodies, town extensions and terrain are not suitable for agriculture. The five different weighting methods used to combine for the four distributed factors are described below. The resulting values are reclassified into GIDD classes for display purposes as shown in Table A2.3 and Figure A2.2 show the results. In all cases, n is the number of factors (n=4), i indicates the factor, W_i is the normalized weight for the factor I, and r_i ranks the importance of the factor i in the combination. Methods W2 and W5 imply a decreasing importance from factor A to D.

W1. Equal weight method

$$W_i = \frac{1}{n}$$

Factors	Normalized Weight
B	0.25
C	0.25
D	0.25
E	0.25
TOTAL	1

W2. Rank sum weighting method

$$W_i = \frac{n - r_i + 1}{\sum_{k=i}^{n}(n - r_k + 1)}$$

Factors	Rank (r)	Normalized weight (W_i)
B	1	0,4
C	2	0,3
D	3	0,2
E	4	0,1
TOTAL		1

W3. Rank reciprocal weighting method:

$$W_i = \frac{{}^{1}/_{r_i}}{\sum_{k=i}^{n}({}^{1}/_{r_k})}$$

Factors	Rank (r)	Normalized weight (W_i)
B	1	0,48
C	2	0,24
D	3	0,16
E	4	0,12
TOTAL		1

W4. Pairwise comparison weighting method:

This method was developed by (Saaty, 1980) and is based on the evaluation of the relative importance between two factors using the following Index value (k):

- 1= same importance
- 3 = slightly more important
- 5= moderately more important
- 7= strongly more important

The grey cells of the table below are completed using the index value and the lower part of the table is completed accordingly using $\frac{1}{k}$ as index value. Cross-factor weights are calculated in the so-called "normalized comparison" matrix according to $CN_{i,j} = \frac{R_{i,j}}{\sum_{j=0}^{n} R_{i,j}} \frac{1}{k}$, and then the individual factor weights are calculated as the mean of each row of the normalized comparison matrix.

	Relative importance of the factors (Ri,j)				**Normalized comparison (CNi,j)**				**Normalized weight (Wi)**
Factors	A	B	C	D	A	B	C	D	
B	1,000	1,000	3,000	5,000	0,395	0,395	0,409	0,357	0,389
C	1,000	1,000	3,000	5,000	0,395	0,395	0,409	0,357	0,389
D	0,333	0,333	1,000	3,000	0,132	0,132	0,136	0,214	0,153
E	0,200	0,200	0,333	1,000	0,079	0,079	0,045	0,071	0,069
TOTAL	2,533	2,533	7,333	14,000	1,000	1,000	1,000	1,000	1,000

Following (Malczewski, 1999), we verified that the obtained weights were consistent, by calculating the consistency ratio (CR=CI/RI with CI = $(\lambda_{max} – n)/(n-1)$, the consistency index of our matrix and CI the consistency index of a random matrix (CI= 0.58 for 3 criteria, 0.9 for 4 and 1.12 for 5) (CR= 0.061 < 0.1).

W5. Rating method:

This method relies on the assignment of a straight rating (Sr) value to each factor, within a scale from 0 to 10 (twice the number of factor), 10 being the most important factor and 0 being the less important one:

$$W_i = \frac{Sr_i \big/ \min\limits_{A \le i \le E} Sr_i}{\sum_{k=i}^{n} \left(1/r_k \right)} = \frac{R_i}{\sum_{k=i}^{n} \left(1/r_k \right)}$$

Factors	**Straight rating (Sr_i)**	**Ratio (R_i)**	**Normalized weight (W_i)**
B	10	2.5	0.345
C	8	2	0.276
D	7	1.75	0.241
E	4	1	0.138

Table A2.2: Summary of the weight applied to each factor according to five weighting methods

Factors	**Equal weight (W1)**	**Rank sum (W2)**	**Rank reciprocal (W)3**	**Pairwise comparison (W4)**	**Rating method (W5)**
A	0,250	0,400	0,480	0,389	0,345
B	0,250	0,300	0,240	0,389	0,276
C	0,250	0,200	0,160	0,153	0,241
D	0,250	0,100	0,120	0,069	0,138

Table A2.3: Ranking of the distributed groundwater irrigation development constraint (GIDD) into classes of constraint.

Value	GIDD class description
1 – 1. 7	Extremely conducive
1.7 – 2.6	Highly conducive
2.6 – 3.4	Moderately conducive
3.4 – 4.2	Slightly conducive
4.2 – 5	Non-conducive

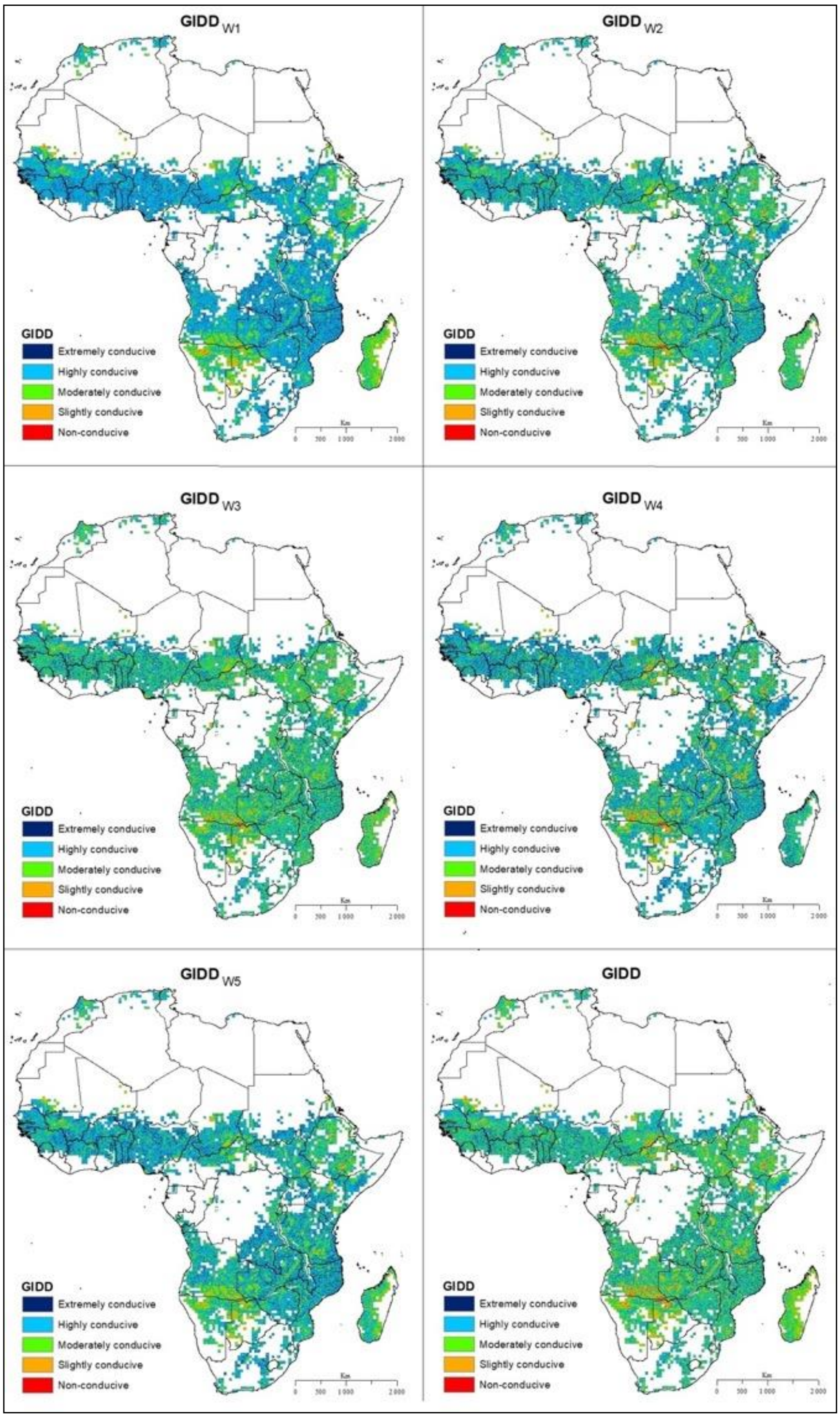


Figure A.2.2: Individual groundwater irrigation development driver (GIDD) estimated by extracting the highest constraint classes from the equal weight method ($GIDD_{W1}$), the ranking sum method ($GIDD_{W2}$), the ranking reciprocal method ($GIDD_{W3}$), the pairwise comparison ($GIDD_{W4}$) and the rating method ($GIDD_{W5}$).

References

Altchenko, Y. and Villholth, K. G. (2015) Mapping irrigation potential from renewable groundwater in Africa – a quantitative hydrological approach. Hydrol. Earth Syst. Sci., 19(2), pp. 1055-1067.

Balk, D. et al. (2006) Determining Global Population Distribution: Methods, Applications and Data. Advances in Parasitology, Volume 62, pp. 119-156.

Droogers, P., Terink, W., Brandsma, J. and Immerze, W. (2012) Assessment of the irrigation potential in Burundi, Eastern DRC, Kenya, Rwanda, South Sudan, Tanzania and Uganda, Wageningen, The Netherlands: Future Water.

Malczewski, J. (1999) GIS and Multicriteria Decision Analysis. New York: John Wiley & Sons.

Saaty, T. L. (1980) The Analytic Hierarchy Process: Planning, Priority Setting, Resource Allocation. Decision Making Series ed. New York: McGraw-Hill International.

Wale, A. et al. (2013) Realistic assessment of irrigation potential in the Lake Tana basin, Ethiopia. Nairobi, ILRI.

Worqlul, A. et al. (2017) Assessing potential land suitable for surface irrigation using groundwater in Ethiopia. Applied Geography, Volume 85, pp. 1-13.

Annex 3: Sensitivity analysis

The results are discussed through three sensitivity analysis tests that highlight the relevance of using all the driving factors, and the uncertainty generated by the methodology.

Test 1: Map removal sensitivity

The first test was performed on the four driving factors to verify that they are relevant for the calculation. In other words, the test identifies whether one factor is dominating the results or if one factor could be removed from the calculation without significantly affecting the results. This test was conducted by performing the map removal sensitivity analysis as defined by Lodwick et al. (1990).

This test calculates GIDD when one factor is removed from the calculation and then, it compares the results to the final GIDD by calculating the Sensitivity Index (SI). SI, expressed as percentage, indicates the variation between the GIDD calculated with four driving factors and the GIDD calculated for three factors only. SI calculation is performed for each cell and for the five weighting methods (W1 to W5), according to the equation:

$$SI = \frac{\left| {GIDD_i}/{N} - {GIDD'_i}/{(N-1)} \right|}{GIDD_i} \times 100$$

where $GIDD_i$ is the GIDD calculated with four driving factor and using weighting method i, GIDD'$_{i}$ is GIDD calculated with three driving factors using weighting method j when one factor has been removed and N the number of factor (i.e.; N=4).

The calculation is done for the five weighting methods (W1 to W5). The Table A3.1 below summarises the weight used for the calculation of the GIDD when removing one factor, while Table A3.2 present the percentage of variation of SI. Regardless of the weighting method, access to market (D) has the highest variation of the GIDD (mean of SI varies between 10.5% and 12.2%). This is probably due to the density of population and to the road network in Africa where there are large pockets of very high constraints with no roads or towns (i.e., Sahara Desert, Kalahari and Namibian desert). Borehole investment (F) seems to be the least sensitive factor (mean of SI varies between 7.1% and 7.8%) while alone, it is the dominant factor driving groundwater irrigation development. This can be explained because it has the lowest weight of all the weighting methods, except for the equal weight method. Overall, SI for the driving factors and the five weighting methods varies from 7.1% to 12.2%, showing no extreme importance of any one factor and sufficient variation for considering the four driving factors in the calculation of the GIDD.

Table A3.1: Summary of the weight applied to the set of diving factor

Removed Factors	**Weighting method**	**Weight on individual driving factors**			
		A	B	C	D
C	Equal weight (W1)	-	0,334	0,333	0,333
	Rank sum (W2)	-	0,500	0,333	0,167
	Rank reciprocal (W)3	-	0,545	0,273	0,182
	Pairwise comparison (W4)	-	0,634	0,260	0,106
	Rating method (W5)	-	0,421	0,368	0,211
D	Equal weight (W1)	0,334	-	0,333	0,333
	Rank sum (W2)	0,500	-	0,333	0,167
	Rank reciprocal (W)3	0,545	-	0,273	0,182
	Pairwise comparison (W4)	0,480	-	0,405	0,115
	Rating method (W5)	0,455	-	0,364	0,182
E	Equal weight (W1)	0,333	0,333	-	0,334
	Rank sum (W2)	0,500	0,333	-	0,167
	Rank reciprocal (W)3	0,545	0,273	-	0,182
	Pairwise comparison (W4)	0,455	0,454	-	0,091
	Rating method (W5)	0,455	0,364	-	0,182
F	Equal weight (W1)	0,334	0,333	0,333	-
	Rank sum (W2)	0,500	0,333	0,167	-
	Rank reciprocal (W)3	0,545	0,273	0,182	-
	Pairwise comparison (W4)	0,429	0,428	0,143	-
	Rating method (W5)	0,400	0,320	0,280	-

Table A3.2: Variation index (%) calculated for the map removal sensitivity analysis.

	Removed parameter	min	max	mean	Standard deviation	Coefficient of variation (%)
Equal weight (W1)	C	0,3	16,7	7,7	4,5	58,6
	D	0,3	16,7	10,9	4,2	38,4
	E	0,3	16,7	9,4	3,9	41,4
	F	0,3	16,7	7,1	4,6	64,6
Rank sum (W2)	C	0,1	24,0	8,7	6,1	70,2
	D	0,0	20,5	11,3	5,2	45,5
	E	0,0	15,8	9,4	3,4	36,2
	F	0,0	13,5	7,8	3,2	41,0
Rank reciprocal (W3)	C	0,0	29,8	9,3	7,1	76,3
	D	0,1	19,3	10,5	4,2	39,9
	E	0,3	13,9	9,1	2,6	28,4
	F	0,3	11,9	7,4	2,8	37,9
Pairwise comparison (W4)	C	0,1	23,4	8,2	5,9	72,0
	D	0,0	29,4	12,2	6,8	55,8
	E	0,1	13,0	8,5	2,8	32,7
	F	1,1	10,9	7,6	2,0	26,0
Rating method (W5)	C	0,0	21,0	8,2	5,4	66,0
	D	0,0	17,8	11,0	4,8	43,1
	E	0,0	16,3	9,2	4,0	43,6
	F	0,4	12,5	7,3	3,0	41,2

Test 2: sensitivity test on the ranking of driving factor crop water need (B) and on the aggregation of levels of conduciveness of the groundwater irrigation development

The second test is performed to determine the level of uncertainty regarding the driving factor of crop water need (B) and from the aggregation of levels of conduciveness of the groundwater irrigation development driver. It calculates GIDP with different threshold values. Tables A3.4 and A3.5 summarize GIDP per country for the driving factors crop water need (B) and for the aggregation of the levels of conduciveness of the groundwater irrigation development, respectively. Figure A3.1 maps GIDP based upon the crop water threshold.

Overall, the primary limiting factor is the irrigation requirement: if the average irrigation requirement is reduced by 100 mm (>400 mm), total GIPD rises from 19.3 10^3 ha to 33.2 10^3 ha (Table A3.5). If the average of irrigation requirement exceeds 300 mm, GIDP reaches the physical irrigation potential calculated by Altchenko and Villholth (2015). The increased areas are mostly located in the equatorial zone where developing and investing in irrigation is unlikely, especially for smallholders because irrigation needs are not sufficient to justify such investment. Figure A3.2 presents GIDP from the aggregation of different classes conduciveness of the groundwater irrigation development. There is a minimal increase in areas where sustainable groundwater irrigation development is favourable if those areas with moderate conduciveness are added to the extremely and highly conducive areas. The most substantial increase is located in Madagascar (Table A3.4). In fact, the availability of sustainable groundwater limits the areas where irrigation can be developed. Not surprisingly, the factor the most conducive to groundwater irrigation development is the water resource itself, which can practically irrigate only those areas with extreme and high conduciveness.

Table A3.4: Sustainable groundwater irrigation development potential (GIDP) depending on several threshold value for the limiting factor irrigation needs

Country	**GIDP (ha)**					
	crop water need (mm)					
	> 200	>300	>400_	>500*_	>600	>700
Algeria	48	48	48	48	45	28
Angola	2887	2887	2379	1671	583	130
Benin	235	235	235	235	233	203
Botswana	23	23	23	23	23	23
Burkina Faso	136	136	136	136	135	114
Burundi	74	74	74	73	38	9
Cameroon	3042	3042	2516	824	176	108
Central African Republic	2656	2656	2219	933	412	267
Chad	249	249	249	249	244	194
Côte d'Ivoire	1208	1208	538	410	325	231
Democratic Republic of Congo	9809	9809	6977	1827	514	120
Djibouti	3	3	3	3	3	3
Egypt	1	1	1	1	1	1
Equatorial Guinea	289	289	288	75	0	0
Eritrea	7	7	6	6	6	6
Ethiopia	1728	1704	1595	1301	933	628
Gabon	2379	2379	1164	54	0	0
Gambia	13	13	13	13	13	13
Ghana	609	609	383	367	237	99
Guinea	1232	1232	1192	1076	724	473
Guinea-Bissau	91	91	91	91	91	77
Kenya	205	205	205	204	189	140
Lesotho	6	6	6	3	1	1
Liberia	994	868	268	0	0	0
Libya	11	11	11	11	11	11
Madagascar	1349	1349	1290	1007	751	445
Malawi	245	245	245	245	244	224
Mali	383	383	383	383	370	263
Mauritania	21	21	21	21	21	21
Morocco	51	51	51	51	51	49
Mozambique	893	893	893	893	855	639
Namibia	38	38	38	38	38	38
Niger	7	7	7	7	7	7
Nigeria	2709	2709	2709	2129	1302	854
Republic of Congo	2916	2916	1170	141	0	0
Rwanda	55	55	55	49	3	0
Senegal	179	179	180	179	180	166
Sierra Leone	652	652	573	304	216	133
Somalia	20	20	20	20	20	20
South Africa	105	105	96	68	55	31
South Sudan	1370	1370	1216	698	381	207
Sudan	201	201	201	201	180	160
Swaziland	9	9	9	8	1	0
Tanzania	1301	1301	1301	1245	1219	891
Togo	126	126	126	126	114	101
Tunisia	9	9	9	9	9	7
Uganda	206	206	207	152	111	73
Western Sahara	0	0	0	0	0	0
Zambia	1644	1644	1645	1584	1263	608
Zimbabwe	140	140	140	140	134	118
TOTAL	**42.5 10^3**	**42.4 10^3**	**33.2 10^3**	**19.3 10^3**	**12.5 10^3**	**7.9 10^3**

*Corresponding to final GIDP

Table A3.5: Sustainable groundwater irrigation development potential (GIDP) depending on several aggregation of class of conduciveness for sustainable groundwater irrigation development (GIDP).

Country **GIDP (10^3 ha)**	**Aggregation of the class of conduciveness**				
	Extremely	Extremely to highly*	Extremely to moderately	Extremely to slightly	Extremely to non
Algeria	16	48	48	48	48
Angola	1108	1671	1698	1699	1699
Benin	248	235	235	235	233
Botswana	7	23	25	25	25
Burkina Faso	136	136	136	135	135
Burundi	17	73	76	76	76
Cameroon	454	824	824	824	824
Central African Republic	710	933	967	967	967
Chad	162	249	262	263	263
Côte d'Ivoire	397	410	410	410	410
Democratic Republic of Congo	1481	1827	1827	1827	1827
Djibouti	0	3	4	4	4
Egypt	0	1	1	1	1
Equatorial Guinea	60	75	77	77	77
Eritrea	3	6	7	7	7
Ethiopia	523	1301	1301	1301	1302
Gabon	12	54	54	54	54
Gambia	13	13	13	13	13
Ghana	363	367	367	367	365
Guinea	643	1076	1076	1077	1077
Guinea-Bissau	83	91	91	91	91
Kenya	191	204	213	213	213
Lesotho	2	3	3	4	4
Liberia	0	0	0	0	0
Libya	0	11	11	11	11
Madagascar	0	1007	1493	1496	1496
Malawi	156	245	253	253	253
Mali	184	383	384	384	384
Mauritania	5	21	24	24	24
Morocco	30	51	51	51	51
Mozambique	836	893	895	896	896
Namibia	8	38	39	39	39
Niger	6	7	7	7	7
Nigeria	1784	2129	2150	2161	2162
Republic of Congo	49	141	200	209	209
Rwanda	8	49	49	49	49
Senegal	151	179	180	180	180
Sierra Leone	192	304	305	305	305
Somalia	12	20	20	20	20
South Africa	45	68	68	68	68
South Sudan	486	698	698	700	700
Sudan	187	203	203	203	203
Swaziland	2	8	8	8	8
Tanzania	993	1245	1254	1254	1254
Togo	115	126	127	127	127
Tunisia	9	9	10	10	10
Uganda	122	152	169	172	172
Western Sahara	0	0	0	0	0
Zambia	1306	1584	1598	1598	1598
Zimbabwe	118	140	140	140	140
TOTAL	**13.4 10^3**	**19.3 10^3**	**20.0 10^3**	**20.1$10^3$**	**20.1 10^3**

*Corresponding to final GIDP

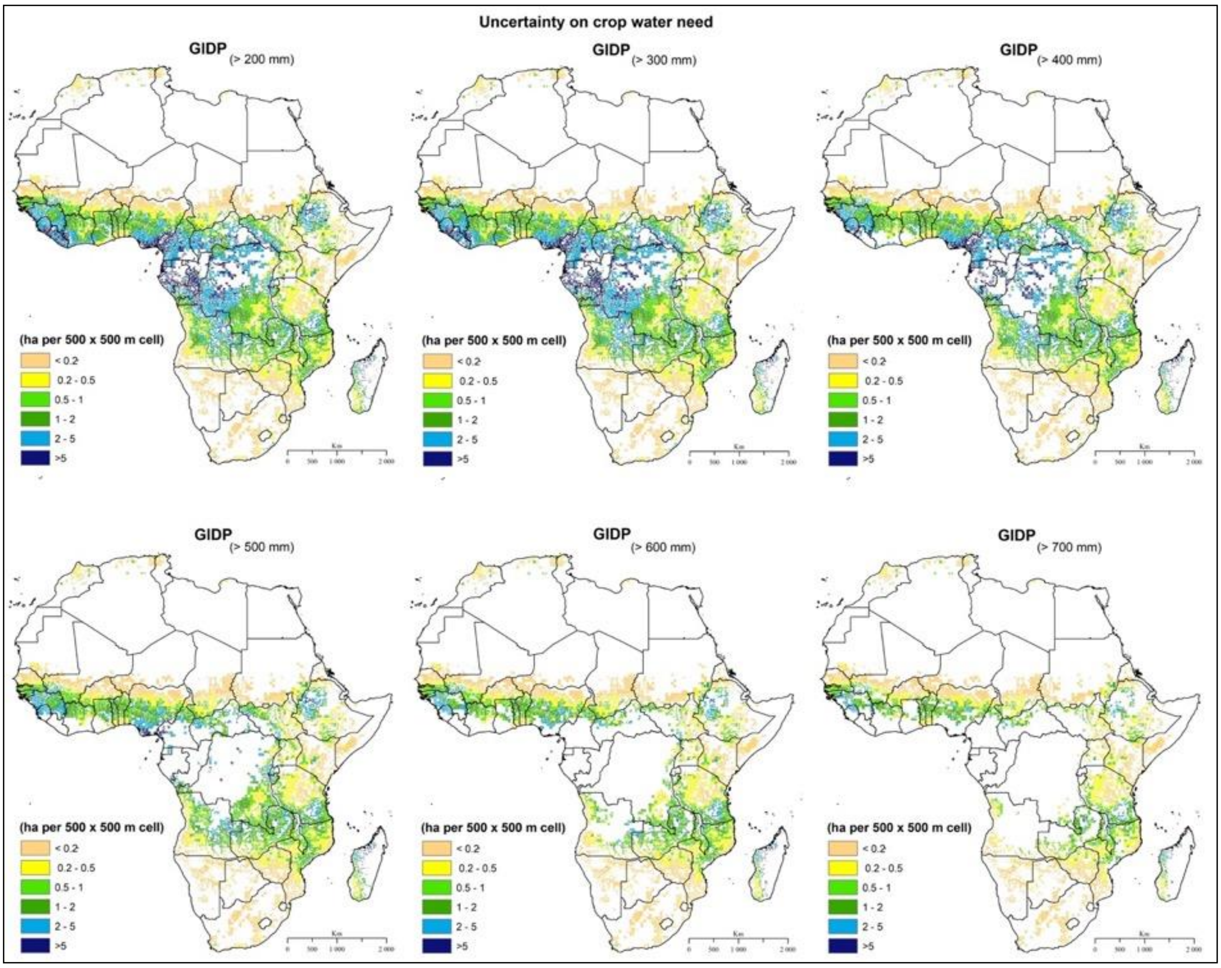


Figure A.3.1: Sustainable groundwater irrigation development potential (GIDP) expressed in hectare per cell at a resolution of 0.005° (cell area about 25 ha) and estimated from several threshold value for the crop water need starting from 200 mm to 700 mm with 100 mm incrementation.

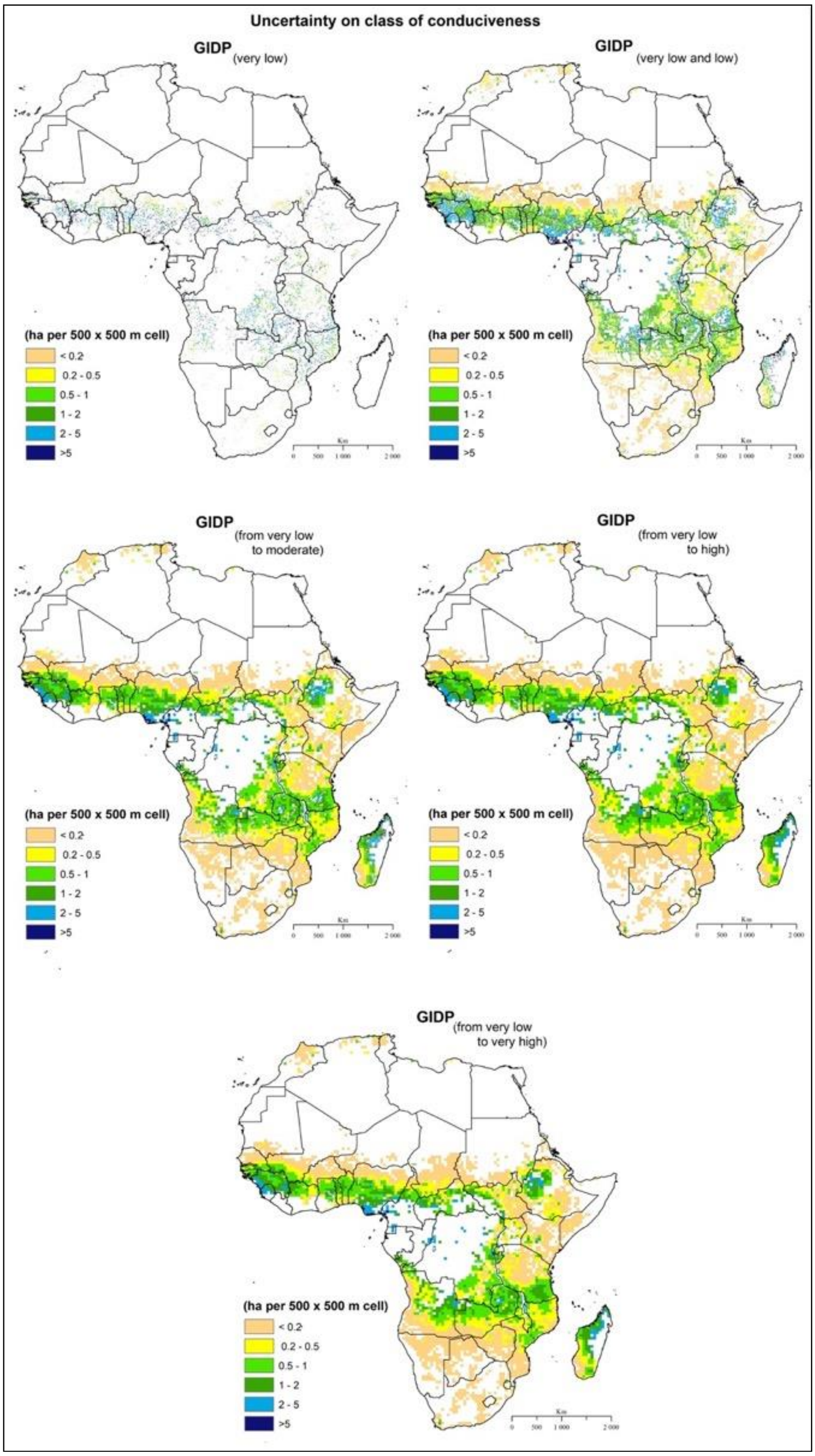


Figure A.3.2: Sustainable groundwater irrigation development potential (GIDP) expressed in hectare per cell at a resolution of 0.005° (cell area about 25 ha) and estimated from the aggregation of the several classes of conduciveness of groundwater irrigation development.

Test 3: sensitivity test on the ranking of driving factor access to surface water (C) and access to market (D)

The third test provides an understanding of the uncertainty generated by the driving factors of access to surface water (C) and access to market (D). These factors are built using three parameters corresponding to the distance to features (rivers, reservoirs, towns, and roads). As the distance to features is binned into five classes of conduciveness, this test examines the uncertainty generated by the rankings. Two additional rankings are performed for each parameter. Thus, there are three different rankings for each parameter. Groundwater irrigation development potential (GIDP) is then calculated by using different combinations. In total, twenty-seven GIDPs are calculated from the twenty-seven possible combinations of the three rankings of each parameter used in determining the GIDD of the driving factor access to surface water (C). Similarly, twenty-seven GIDPs are calculated for the driving factor of access to market (B). The section below shows the different combinations for the two driving factors.

Access to surface water (C)

The driving factor access to surface water depends on three parameters correspond to the distance to Perennial River (PR), Intermittent River (IR) and Water Bodies (WB). The three parameters are ranked into the five classes of conduciveness according to three different rankings, $GIDD_C$ is calculated using the twenty-seven combinations and GIDP is calculated applying the five weighting methods and using the twenty-seven $GIDD_C$ as presented in the tables below. The initial ranking system for parameters D, E and F is used in the calculation.

Perennial Rivers (PR)			
Test name	PR1	PR2	PR3
Conduciveness class	Distance (km)	Distance (km)	Distance (km)
5	0 – 1	0 – 2	0 – 5
4	1 – 3	2 – 5	5 – 10
3	3 – 5	5 – 10	10 – 15
2	5 – 10	10 – 15	15 – 20
1	> 10	> 15	> 20

Intermittent rivers (IR)			
Test name	IR1	IR2	IR3
Conduciveness class	Distance (km)	Distance (km)	Distance (km)
5		0 – 1	
4		1 – 3	
3	1 – 5	3 – 5	2 – 10
2	5 – 10	5 – 10	10 – 20
1	0 – 1 and > 10	> 10	0 – 2 and > 20

Water bodies (WB)			
Test name	WB1	WB2	IR3
Conduciveness class	Distance (km)	Distance (km)	Distance (km)
5	0 – 2	0 – 5	0 – 10
4	2 – 5	5 – 10	10 – 20
3	5 – 10	10 – 15	20 – 30
2	10 – 15	15 – 20	30 – 40
1	> 15	> 20	> 40

Combination number	Perennial Rivers	Intermittent rivers	Water bodies
A01	PR1	IR1	WB1
A02	PR1	IR1	WB2
A03	PR1	IR1	WB3
A04	PR1	IR2	WB1
A05	PR1	IR2	WB2
A06	PR1	IR2	WB3
A07	PR1	IR3	WB1
A08	PR1	IR3	WB2
A09	PR1	IR3	WB3
A10	PR2	IR1	WB1
A11	PR2	IR1	WB2
A12	PR2	IR1	WB3
A13	PR2	IR2	WB1
A14	PR2	IR2	WB2
A15	PR2	IR2	WB3
A16	PR2	IR3	WB1
A17	PR2	IR3	WB2
A18	PR2	IR3	WB3
A19	PR3	IR1	WB1
A20	PR3	IR1	WB2
A21	PR3	IR1	WB3
A22	PR3	IR2	WB1
A23	PR3	IR2	WB2
A24	PR3	IR2	WB3
A25	PR3	IR3	WB1
A26	PR3	IR3	WB2
A27	PR3	IR3	WB3

Access to surface market (D)

The driving factor access to market depends on three parameters correspond to the distance to town inferior at 50000 inhabitants (InfTown), town superior at 500000 inhabitants (SupTown) and Road (Road). The three parameters are ranked into the five classes of conduciveness according to three different rankings, GIDD$_D$ is calculated using the twenty-seven combinations and GIDP is calculated applying the five weighting methods and using the twenty-seven GIDD$_D$ as presented in the tables below. The initial ranking system for parameters C, E and F is used in the calculation.

Town < 50000 inhabitants (InfTown)

Test name	InfTown1	InfTown2	InfTown3
Conduciveness class	Distance (km)	Distance (km)	Distance (km)
5	> 50	> 30	> 80
4	30 – 50	20 – 30	60 – 80
3	20 – 30	10 – 20	40 – 60
2	10 – 20	5 – 10	20 – 40
1	0 – 10	0 – 5	0 – 20

Town > 500000 inhabitants (SupTown)

Test name	SupTown1	SupTown2	SupTown3
Conduciveness class	Distance (km)	Distance (km)	Distance (km)
5	> 100	> 50	> 120
4	60 – 100	30 – 50	90 – 120
3	60 – 40	20 – 30	60 – 90
2	40 – 20	10 – 20	30 – 60
1	0 – 20	0 – 10	0 – 30

Road (Road)

Test name	Road1	Road2	Road3
Conduciveness class	Distance (km)	Distance (km)	Distance (km)
5	> 20	> 50	> 15
4	15 – 20	30 – 50	10 – 15
3	10 – 15	20 – 30	5 – 10
2	5 – 10	10 – 20	2 – 5
1	0 – 5	0 – 10	0 – 2

Combination number	Perennial Rivers	Intermittent rivers	Water bodies
D01	InfTown1	SupTown1	Road1
D02	InfTown1	SupTown1	Road2
D03	InfTown1	SupTown1	Road3
D04	InfTown1	SupTown2	Road1
D05	InfTown1	SupTown2	Road2
D06	InfTown1	SupTown2	Road3
D07	InfTown1	SupTown3	Road1
D08	InfTown1	SupTown3	Road2
D09	InfTown1	SupTown3	Road3
D10	InfTown2	SupTown1	Road1
D11	InfTown2	SupTown1	Road2
D12	InfTown2	SupTown1	Road3
D13	InfTown2	SupTown2	Road1
D14	InfTown2	SupTown2	Road2
D15	InfTown2	SupTown2	Road3
D16	InfTown2	SupTown3	Road1
D17	InfTown2	SupTown3	Road2
D18	InfTown2	SupTown3	Road3
D19	InfTown3	SupTown1	Road1
D20	InfTown3	SupTown1	Road2
D21	InfTown3	SupTown1	Road3
D22	InfTown3	SupTown2	Road1
D23	InfTown3	SupTown2	Road2
D24	InfTown3	SupTown2	Road3
D25	InfTown3	SupTown3	Road1
D26	InfTown3	SupTown3	Road2
D27	InfTown3	SupTown3	Road3

Results

Table A3.6 presents the minimum, maximum, mean, and standard deviation from the twenty-seven GIDPs, while Figure A3.3 shows the mean and standard deviation from the twenty-seven GIDPs calculated for access to surface water (C) and access to market (D). The results show that access to surface water (A) has a relatively significant uncertainty with above 12% as average of the coefficient of variation. It seems that there is a direct impact of the ranking on the final GIDP. This result mirrors the fact that access to surface water is the dominant driving factor: variation in the ranking generates variation in the final results. Most of the uncertainty is located in the perennial river zones where there are higher constraints on groundwater irrigation development. The GIDP seems to be close to the maximum of the twenty-seven GIDPs, appearing at the upper end of the calculation. In contrast, there is little uncertainty from access to market (D) with the average of the coefficient of variation at about 1% (maximum 13% for Lesotho). This is consistent with the statistics of driving factors which indicate that access to market is the least dominant factor. While limited in scope, uncertainties occur along two east-west lines: from south of Tanzania to Angola and from west of Ethiopia to Gambia, inside the perennial river zone.

Table A3.6: Sustainable groundwater irrigation development potential (GIDP) calculated with several combinations which build the driving factor access to surface water (A) and access to market (B)

Country	**This study GIDP (10^3ha)**	**Uncertainty on factor A GIDP (10^3ha)**				**Uncertainty on factor B GIDP (10^3ha)**			
		MIN	MAX	MEAN	STD	MIN	MAX	MEAN	STD
Algeria	48	35	48	45	3,8	48	48	48	0,1
Angola	1671	1160	1671	1498	231,9	1665	1671	1678	15,2
Benin	235	235	247	240	4,3	235	247	236	0,7
Botswana	23	21	23	22	0,7	22	23	23	1,0
Burkina Faso	136	135	138	137	1,1	135	138	136	0,4
Burundi	73	21	73	55	19,9	73	73	74	0,9
Cameroon	824	488	824	709	134,1	822	824	823	1,8
Central African Republic	933	737	933	851	83,4	905	933	937	18,0
Chad	249	172	251	222	32,1	247	251	253	5,1
Côte d'Ivoire	410	391	411	408	6,2	410	411	410	0,2
Democratic Republic of Congo	1827	1507	1827	1716	126,5	1818	1827	1825	3,9
Djibouti	3	3	5	4	0,9	3	5	3	0,1
Egypt	1	0	1	1	0,5	1	1	1	0,0
Equatorial Guinea	75	69	75	73	3,0	75	75	76	0,2
Eritrea	6	5	6	6	0,3	6	6	6	0,0
Ethiopia	1301	736	1301	1110	251,1	1301	1301	1301	1,5
Gabon	54	13	62	41	20,2	44	62	52	4,7
Gambia	13	10	13	11	1,1	13	13	13	0,1
Ghana	367	365	367	366	1,2	367	367	367	0,6
Guinea	1076	719	1077	964	160,6	1076	1077	1076	1,0
Guinea-Bissau	91	85	93	90	3,3	91	93	91	0,1
Kenya	204	201	205	202	1,0	204	205	204	0,4
Lesotho	3	2	7	4	1,6	3	7	3	0,4
Liberia	0	0	0	0	0,0	0	0	0	0,0
Libya	11	10	11	11	0,0	11	11	11	0,0
Madagascar	1007	91	1007	511	315,0	919	1007	990	47,0
Malawi	245	159	245	204	31,8	240	245	245	2,0
Mali	383	244	383	335	62,6	383	383	383	0,5
Mauritania	21	20	21	21	0,2	20	21	21	0,5
Morocco	51	45	51	49	2,3	51	51	51	0,0
Mozambique	893	843	895	878	21,6	885	895	892	4,9
Namibia	38	32	38	36	1,8	36	38	38	1,1
Niger	7	7	7	7	0,2	7	7	7	0,1
Nigeria	2129	1799	2129	2004	122,5	2090	2129	2128	18,4
Republic of Congo	141	51	141	108	33,2	130	141	143	5,3
Rwanda	49	11	49	31	15,1	47	49	50	0,6
Senegal	179	169	180	177	4,0	179	180	179	0,3
Sierra Leone	304	198	304	271	46,1	304	304	304	0,3
Somalia	20	20	20	20	0,1	20	20	20	0,1
South Africa	68	45	69	61	8,6	67	69	67	0,4
South Sudan	698	516	698	639	72,1	686	698	696	4,3
Sudan	203	197	203	202	3,6	201	203	201	0,8
Swaziland	8	2	8	7	1,7	8	8	8	0,0
Tanzania	1245	1028	1245	1150	79,7	1211	1245	1240	13,1
Togo	126	117	126	123	2,8	126	126	126	0,3
Tunisia	9	9	10	10	0,3	9	10	9	0,1
Uganda	152	126	152	143	7,6	149	152	152	1,1
Western Sahara	0	0	0	0	0,0	0	0	0	0,0
Zambia	1584	1324	1584	1483	92,5	1563	1584	1584	13,8
Zimbabwe	140	122	140	136	5,4	140	140	140	0,3
TOTAL	**19.3 10^3**	**14.3 10^3**	**19.4 10^3**	**17.4 10^3**		**19.0 10^3**	**19.4 10^3**	**19.3 10^3**	

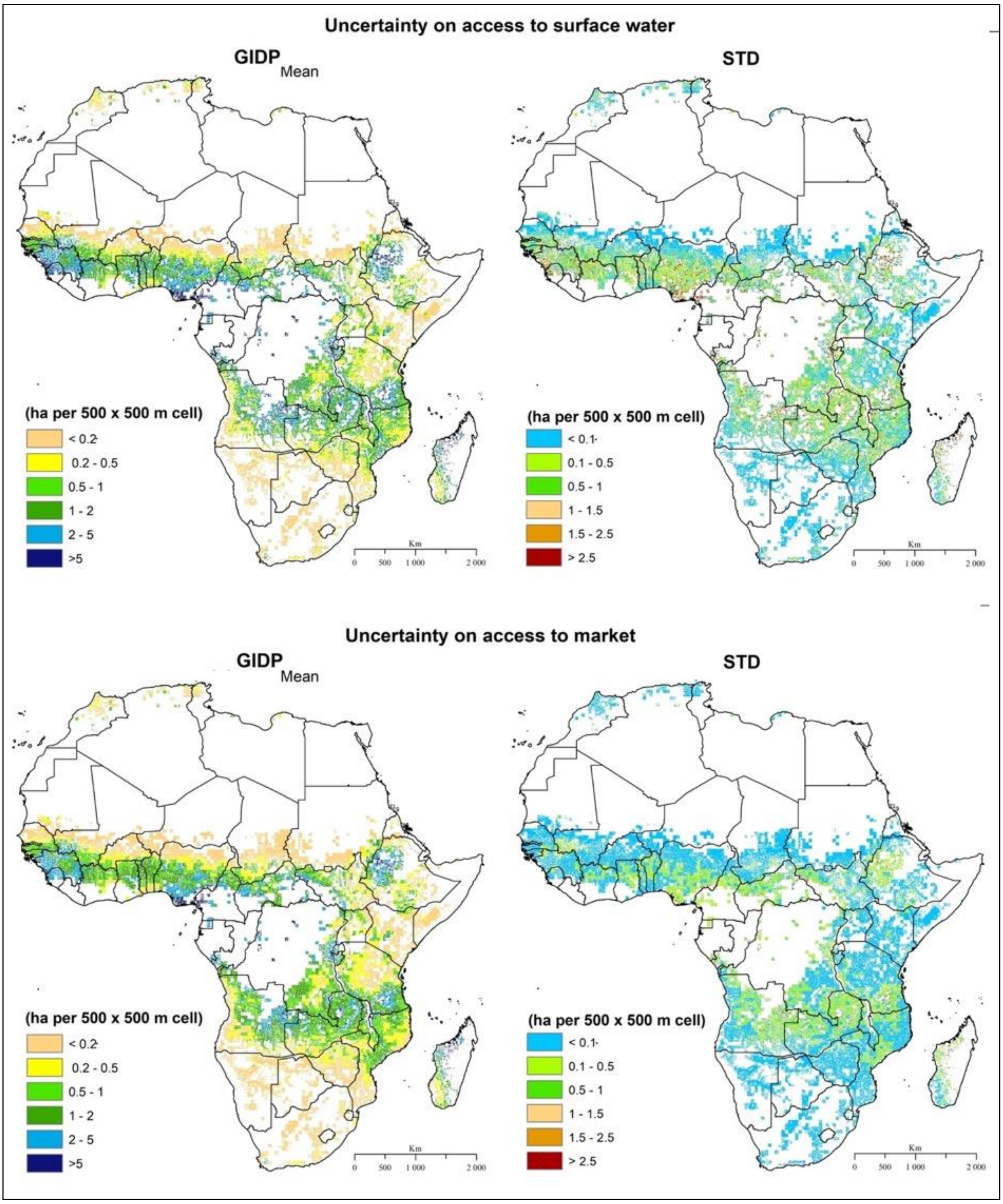


Figure A3.3: Mean and standard deviation (STD) corresponding to the sensitivity analysis on access to surface water (C) and access to market (D), respectively, both expressed in hectare per cell at a resolution of 0.005° (cell area about 25 ha).

Table of figures

Table of Tables

Abstract:

In Africa, groundwater irrigation is considered a reliable and affordable means to increase food security. Areas equipped for groundwater irrigation in Africa have however, developed slowly since 1950 and remain very limited. To date, no studies have identified the sustainable development potential of irrigation with renewable groundwater across Africa. This study is based on two approaches to locate and quantify this potential. The quantitative hydrological approach is based on the estimation of the current crop irrigation need and available renewable groundwater for irrigation after all other water needs, including environmental, have been satisfied. This approach shows that the potential is 44.6 x 10^6 ha or 20.5% of the cropland over the continent. The environmental approach redefines the quantitative potential by considering a set of biophysical and socio-economic factors conducive to sustainable development of groundwater irrigation. The potential is then 19.3 x 10^6 ha and it is reduced mainly from the equatorial regions where the need for irrigation is limited. In fact, without considering the countries of the Maghreb and South Africa where current irrigation by groundwater exceeds the estimated potential, groundwater irrigated areas could be multiplied by 75. The largest areas which are worthwhile to develop are mainly located along a west-east line from Angola to the north of Mozambique and a line south of the Sahel. The dry regions of the Sahel, East Africa and Southern Africa have limited development potential which is more suitable to small-scale agriculture and could greatly improve food security in Africa.

Keywords: [Africa; irrigation; groundwater; development; sustainable; mapping]

Cartographie du potentiel de développement de l'irrigation durable avec des eaux souterraines renouvelables en Afrique pour réduire l'insécurité alimentaire africaine

Résumé :

En Afrique, l'irrigation des cultures par les eaux souterraines est considérée comme un outil fiable et abordable pour augmenter la sécurité alimentaire mais les superficies équipées pour l'irrigation par les eaux souterraines restent très limitées. Cette étude se base sur deux approches pour localiser et quantifier le potentiel de développement de l'irrigation des cultures par les eaux souterraines renouvelables sur l'ensemble du continent. L'approche quantitative et hydrologique s'appuie sur l'estimation des eaux souterraines renouvelables disponibles après satisfaction de tous les autres besoins, y compris environnementaux et sur le besoin en irrigation des cultures et montre un potentiel s'élevant à 44.6 x 10^6 ha soit 20.5% des cultures du continent. L'approche contextuelle redéfinit le potentiel quantitatif en considérant un ensemble de facteurs biophysiques et socio-économiques propices au développement de l'irrigation par les eaux souterraines. Le potentiel s'élève alors à 19,3 x 10^6 ha et est réduit essentiellement dans les régions équatoriales où le besoin en irrigation est limité. En fait, sans considérer les pays où l'irrigation actuelle par les eaux souterraines excède le potentiel estimé, les surfaces irriguées pourraient être multipliées par 75. Les plus grandes surfaces propices au développement de l'irrigation sont principalement situées le long d'une ligne ouest-est de de l'Angola au nord du Mozambique et d'une ligne au sud du Sahel. Les régions sèches du Sahel et de l'Afrique de l'Est et australe ont un potentiel de développement plus limité, plus adapté à la petite agriculture, qui pourrait améliorer amplement la sécurité alimentaire en Afrique.

Mots clés : [Afrique; irrigation; eaux souterraines; développement; durable; cartographie]

Yvan Altchenko – Thèse de doctorat - 2018