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Environmental Technology & International Affairs

Anthropogenic Drivers of Municipal Water Supply: Examining the Impact on Energy Intensity in Water Utilities across Countries in Africa

A Master's Thesis submitted for the degree of
"Master of Science"

supervised by
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Affidavit

I, **MARIA WIRTH**, hereby declare

1. that I am the sole author of the present Master's Thesis, "ANTHROPOGENIC DRIVERS OF MUNICIPAL WATER SUPPLY: EXAMINING THE IMPACT ON ENERGY INTENSITY IN WATER UTILITIES ACROSS COUNTRIES IN AFRICA", 82 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
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Abstract

Energy use for municipal water supply is often responsible for underestimated costs and carbon emissions. Meanwhile, infrastructure managers are struggling to keep up with population growth, economic development and the effects of climate change. Energy intensity of raw water extraction, drinking water purification and distribution depend on a host of supply-side drivers, while cumulative energy use rises with the volume of municipal water that water utilities must produce to meet growing demand. The present study is the first to link drivers of water availability, quality and demand to energy intensity in water utilities. The benefit of the following approach is that country-level impacts are measured as a compound of all identified human-caused drivers under consideration of their interdependencies and feedback mechanisms. A host of anthropogenic supply and demand-side drivers of municipal water and their interdependencies are identified, as well as how they feed into energy intensity in drinking water utilities. Based on the flow model that illustrates how identified drivers interact, ten key indicators are defined to measure levels of impact and country-specific sets of risks. The analytical framework based on these findings is applied to countries in Africa. A continent-wide high impact was found to be caused by competition for freshwater and polluting effluents from agriculture and to a lesser degree from industry. The results also suggest that demand for municipal water is expected to surge in most countries, while the high disparity between wastewater collection and treatment has a strong detrimental effect on surface water quality. The influence caused by drivers of water quality depends on the relative dependency on surface water or groundwater, which indicates the sources accessed for municipal water use. Finally, the countries were clustered according to similar combinations of impacts, where five clusters and three outlying cases were identified. Policymakers and water utility operators can incorporate these findings into their planning considerations in order to build resilient infrastructure and minimise the environmental footprint.

Key words: water-energy nexus, municipal water supply, energy intensity, anthropogenic drivers, water extraction, water treatment, water demand

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List of Abbreviations

AGO	Angola
BDI	Burundi
BEN	Benin
BFA	Burkina Faso
BWA	Botswana
CAF	Central African Republic
CIV	Ivory Coast
CMR	Cameroon
COD	Democratic Republic of the Congo
COG	Republic of Congo
COM	Comoros
CPV	Cape Verde
DJI	Djibouti
DZA	Algeria
EGY	Egypt
ERI	Eritrea
ETH	Ethiopia
GAB	Gabon
GHA	Ghana
GIN	Guinea
GMB	Gambia
GNB	Guinea-Bissau
GNQ	Equatorial Guinea
KEN	Kenya
LBR	Liberia
LBY	Libya
LSO	Lesotho
MAR	Morocco
MDG	Madagascar
MLI	Mali
MOZ	Mozambique
MRT	Mauritania
MUS	Mauritius
MWI	Malawi
NAM	Namibia
NER	Niger
NGA	Nigeria
RWA	Rwanda
SDN	Sudan
SEN	Senegal
SLE	Sierra Leone
SOM	Somalia
SSD	South Sudan
SWZ	Swaziland
TCD	Chad
TGO	Togo
TUN	Tunisia
TZA	Tanzania
UGA	Uganda
ZAF	South Africa
ZMB	Zambia
ZWE	Zimbabwe

1. Introduction

Access to clean drinking water is a basic human right. It is essential to human health and the economic development of societies. Yet, clean water scarcity is among the greatest global challenges of mankind as 748 million people rely on unprotected dug wells, tanker trucks, or bottled water, according to the United Nations World Water Assessment Programme (WWAP 2014b). Thousands of women and children are forced to walk several hours a day to reach the closest source of freshwater, which may still be heavily contaminated. The African continent uniquely suffers from water scarcity across its entire area. Physical water scarcity is a phenomenon in the arid far northern and southern parts, while the majority of African countries face economic water scarcity (WWAP 2014a). Here, renewable freshwater recharge is sufficient to cover human and ecosystem demand, but malnutrition and public supply shortages exist due to financial limitations and mismanagement of the human-hydrological interface. Several countries in sub-Saharan Africa are even experiencing a decrease in access to improved water sources, according to the World Bank World Development Indicators (World Bank 2016).

The delivery of potable water is subject to environmental and technical constraints, exacerbated by global trends such as climate change and population growth. Higher average temperatures, land use change, higher industrial, agricultural and domestic demand for raw water are distorting freshwater availability and driving up operational costs of municipal water utilities (Lubega et al. 2013; Santhosh et al. 2014). Especially in regions struggling to meet rising demand, the cost factor energy is significant. Water-stressed countries have to withdraw water from greater depths or exploit alternative freshwater sources, such as seawater desalination or wastewater recycling. These are by far the most energy-intensive supply choices. Venkatesh et al. (2014) found that energy can account for up to 80% of the costs to purify and distribute potable water. Globally, 8% of total energy generation is used for pumping, treating and transporting water to users, according to the Joint Monitoring Programme for Supply and Sanitation (JMP 2014). The water sector is a major user of energy, even for conventional sources.

Municipal water supply is impossible without energy input. Energy is needed for water production, treatment, distribution, end-use and disposal or recycling. Per unit energy requirements vary wildly across the world. According to Liu et al. (2012), energy constitutes the largest controllable operational cost factor in most water utilities. In order to minimize energy intensity, managers have to quantify and assess implications of water supply sources on energy use. Early planning improves the robustness and lifetime of infrastructure and supports the development of technical solutions that can successfully cope with rapidly growing demand and resource scarcity. Considering that African countries such as South Africa and Botswana produce 94% and 87% of their electricity from coal, respectively (CIA 2016), structural energy efficiency measures translate directly to climate change abatement.

The relationship between the two systems is known as the water-energy nexus. Water is used in fuel production and energy generation, while engineered water infrastructure consumes electricity. Additional energy requirements for water management facilities must be supplied, which in turn may be water-intensive. If water and energy resources are managed without considering their interdependencies, scarcity in either sector may lead to shortages in both. The growing awareness of the potential for efficient resource use and climate action has earned nexus perspectives a prominent position in the post-2015 Development Agenda of the United Nations. The 17 Sustainable Development Goals (SDGs) call for integrated management to ensure that water and energy policies are coherent (General Assembly Resolution 70/1 2015).

However, the regions suffering most from environmental and socio-economic pressures are developing countries, where data availability is limited. This makes careful planning very difficult. Currently, infrastructure planners and policymakers can draw on a number of empirical studies that provide observed energy intensities in engineered water systems, both for utilities and regions under particular conditions. However, they concentrate on regional specifics. Drivers of energy requirements for public water supply have been studied far less. Knowledge of systemic pressures to water infrastructure is essential for managers to plan resilient supply. Technical efficiency increases of energy-using devices along the water supply chain are levelling, which emphasises the need to examine how drivers of drinking water supply sources and demand influence energy use in extraction, treatment and distribution of municipal water. Connecting the environmental and socio-economic systems to technical processes enables planners to conduct long-term cost and resource optimisation.

The present study will identify systemic drivers and examine how they impact energy intensity of municipal water supply. Based on this, the study will provide an analytical framework by which to examine the set of pressures specific to countries. The study will focus on Africa due to the range of climatic zones and corresponding water availability as well as its urgent need for safe water supply at reduced costs. Further, long-term reliability of public services is largely challenged by limited economic capacity and rapid population growth in many countries. A country-level analysis is implemented, because water services and much of the institutional data are typically within centralized planning and control. A cluster analysis will yield groups of countries facing similar pressures and identify outlier cases along with their characteristics. An examination of optimal partition and patterns in the available data may yield useful policy recommendations for knowledge and technology sharing to tackle structural pressures. Policymakers, infrastructure planners and water utility operators can incorporate this framework into their planning considerations.

2. Literature Review

2.1. THE WATER-ENERGY NEXUS

Population growth and changing consumption patterns are driving both global energy and water demand, while electricity-intensity in water supply as well as water-intensity of electricity supply are increasing (Lubega and Farid 2014). The first one to coin the water-energy nexus was Gleick (1994), who described both the water-for-energy and energy-for-water relationship in California. The body of research on the water-energy nexus has since steadily increased. It spans technical efficiency increases, policy options and empirical assessments of energy-intensity along the water life cycle for multiple sectors, including municipal or domestic, industrial and agricultural use, as well as water-intensity of energy supply and environmental impacts.

There are a number of studies calling for nexus-consistent planning of public services to achieve more efficient resource use, satisfy growing demand in a sustainable way as well as to withstand environmental pressures, such as climate change. (e.g. Bazilian et al. 2011; Lubega and Farid 2013; Yillia 2016) The energy-for-water dimension refers to the, often underestimated, energy requirements to convert surface water and groundwater to a supply good for potable use, irrigation or industrial processes to deliver it to end-users and manage waste. The energy sector demands water primarily in fuel production and electricity generation (Siddiqi and Anadon 2011). Mining, processing and transporting fossil fuels requires large amounts of process water. Thermoelectric generation needs large quantities of water for cooling, depending on the heat exchange method and the loop system in water-based cooling systems. Enhanced regulations to limit air pollution drive up water use for flue gas scrubbing. Biofuels pose the transition to the third dimension of the more complete water-energy-food nexus. Biofuel cultivation competes with food production for both land and water. The three-way resource competition is often significant, considering the global amount of water pumped for irrigation. As indicated by Bazilian et al. (2011), irrigation accounts for 15-20% of total electricity use in India.

Competing demand for scarce resources often means a trade-off, but the nexus perspective in policy, planning and operations allows making use of potential synergies. The United Nations World Water Development Report for 2014 (WWAP 2014a) was dedicated to the water-energy nexus, describing water requirements for energy generation and energy requirements for water supply and wastewater management. Prepared by 27 UN organizations, the report emphasizes the need for consistent planning of water and energy infrastructure in order to expand public services to deprived communities and keep up with growing demand. The report also outlines systemic pressures to water supply and demand, water demand in the energy sector, cross-cutting policy implications and opportunities for technical and structural efficiency increases, emphasizing the need to examine systemic drivers.

A growing number of researchers have set up integrated frameworks and put together coupled model tools to optimize energy and water resource use, e.g. TIAM-FR created by Dubreuil et al. (2013) and CLEW (climate, land-use, energy and water strategies) by Howells et al. (2013). They enable the analysis of the impact of water and energy policies affecting structural changes to meet agricultural, industrial and municipal water demand. The water module considers a variety of water supply options and their varying energy intensities. Perrone et al. (2011) developed the 'water-energy nexus model' (WEN), with which energy requirements for water extraction, treatment and discharge as well as volume of water used in energy generation can be calculated.

2.2. ENERGY-FOR-WATER IN MUNICIPAL WATER UTILITIES

2.2.1. Empirical measurements of energy intensity

Water requirements for power generation are studied much more extensively than energy for water. (Nair et al. 2014) But recent years have seen a relative shift in attention. The body of research on the energy intensity of water services spans qualitative descriptions of the stages at which energy is required and technical parameters determining energy intensities, empirical studies that disaggregate and analyze technical efficiency as well as case studies calculating energy required for pumping and treatment at various stages of water and wastewater utilities. Several tools have been developed for water managers to disaggregate and analyze technical and environmental issues with an urban energy-for-water perspective. Several thorough studies exist, which compare and analyze the bulk of previously existing empirical studies on the scale of water technologies, utilities, and regional assessments (e.g. Kenway et al. 2011; Lundie et al. 2004; Plappally and Lienhard 2012; Barry 2007).

Essentially two energy-consuming processes run the water supply chain: pumping and treatment. Energy intensity for freshwater extraction depends on the conditions at the source, including terrain or slope of the pipeline, pump efficiency and piping distance. Energy use for treatment depends on contaminant types and concentrations as well as the selection of treatment processes (WWAP 2014b; Plappally and Lienhard 2012; Cooley and Wilkinson 2012). Technical conditions will be discussed in chapter 4.2.

The broad range of empirical studies provides representative values of energy intensity measured by unit water, primarily kWh/m^3, for given regional and technical conditions. The following table displays examples of energy intensities in previous studies. The list is not comprehensive, but showcases a high degree of variation.

Table 1: Reported energy intensities of water supply at various stages and in different regions. (*These values are given in kWh/year.)

Water supply stage	Region	Purpose	Energy use (kWh/m^3)	Reference
Surface water extraction/ pumping	USA	SW extraction	0	Cooley and Wilkinson 2012
	Western China	Pumping of water over 450 km pipeline	7.1×10^9 *	Marsh 2008
	Ontario, Canada	Pumping	5.55×10^9 *	Maas 2010
Groundwater extraction	California, USA	groundwater pumping	0.14–0.69	Plappally and Lienhard 2012
	Australia	groundwater pumping	0.48–0.53	Rocheta and Pearson 2011
	Arizona, USA	Lifting groundwater	3.3	Perrone et al. 2011
Conventional water treatment	Global	UV disinfection	0.01-0.04	WWAP 2014b
	USA	low value for plant capacity >20 MG/d	0.03	Cooley and Wilkinson 2012
	USA	low value for plant capacity <1MG/d	0.16	Cooley and Wilkinson 2012
	USA	Groundwater treatment	0.19	Goldstein and Smith 2002
	USA	Surface water treatment plant producing 38k m3/d	0.37	Goldstein and Smith 2002
	USA	Surface water treatment plant producing 3,785 m3/d	0.39	Goldstein and Smith 2002
	USA	high value for plant capacity <1MG/d	0.53	Cooley and Wilkinson 2012
Desalination	Global	Reverse Osmosis	1.5-3.5	WWAP 2014b
	USA	Reverse Osmosis	3-5	Goldstein and Smith 2002
	Australia	Seawater desalination	4	Rocheta and Pearson 2011
	USA	Multistage Flash Distillation	10-20	Goldstein and Smith 2002
Water distribution	California, USA	Surface water conveyance over varied terrain	0.028	Cooley and Wilkinson 2012
	California, USA	Surface water conveyance over hilly terrain	0.32	Cooley and Wilkinson 2012
	USA	Imported water conveyance	0.5-1.4	Cooley and Wilkinson 2012
	California, USA	water conveyance and distribution	2.4	California Energy Commission 2005
	Tijuana, Mexico	drinking water conveyance	4.5	Scott et al. 2009

The table illustrates that the variation of energy intensity depends primarily on the definition of boundaries for every stage and the conditions pertaining to the water source selection rather than the region that is analyzed. For example, Cooley and Wilkinson (2012) define source extraction as the vertical pumping, i.e. they consider it separately from conveyance, which is the pipeline from the point of extraction to treatment plants. The distribution stage reveals the highest variance, which is due to large differences of piping distance and terrain (Ibid). Numbers are available for all stages and processes, but they are difficult to generalize due to their dependence on a large number of factors.

2.2.2. Environmental footprint and potential for energy optimisation

Depending on the power mix in a given region or facility, technical processes along the municipal water life cycle are linked to environmental effects, namely air pollution and greenhouse gas emissions. Particularly in Australia, water-energy nexus studies are focusing on the reduction of carbon emissions from the water sector as a strategy for climate change mitigation (Nair et al. 2014). Models centered on this issue include “Water-to-Air” models, with which authors have proven that water use efficiency bears a large potential to reduce air pollution and water supply costs by saving energy (e.g. Wilkinson and Kost 2006; Wolff et al. 2004; Yillia 2016).

Emissions can be reduced by powering the water sector with low-carbon energy sources. But the cleanest energy is that which is not used. Several authors have suggested measures to improve the technical performance of energy-consuming devices (e.g. Raluy et al. 2005; Udono 2005; Nair et al. 2014), e.g. by reducing pipe friction, which lowers pumping energy requirements, or by replacing old devices with new high-efficiency pumps and motors. Fishbein (2014) suggests to minimize leakages, automate system operations and regular monitoring. Another measure is the removal of non-essential valves (Barry 2007). To forego challenges to efficiency posed by elevation changes and long piping distances from source to end-user is another option. Burn et al. (2012) see a strong benefit in decentralized water systems for areas marginalized by topographic or economic limitations. With the optimal conditions, gravity alone transports water across some conveyance systems (Cooley and Wilkinson 2012). Other studies focus on how to retrieve energy from a water supply system, particularly at the water conveyance and distribution stages. A report by the Stanford University’s Water in the West program (Yang and Yamazaki 2013) streamlines previous research on energy-recovery by using excess pressure to generate electricity, i.e. to install in-conduit micro-hydroelectric plants. Campbell (2010) replaces pressure-reducing valves (PRVs) in water transport lines with pumps to transform excess fluid pressure into electricity.

Nair et al. (2014) find that most studies have focused on energy requirements at the wastewater treatment stage and desalination plants. The water-energy nexus is centered on maximizing sustainability and robustness of engineered water systems and the two mentioned processes are the most energy-intensive segments along the urban water life cycle. However, there is hardly scope to further lower energy consumption of desalination processes and recent technical efficiency increases are leveling, limited by thermodynamics (e.g. Elimelech and Phillip 2011; Shatat et al. 2013). This is only one example for technical limitations, which call for a more systemic approach to limit energy consumption induced by the water sector. Nexus-consistent policymaking is challenged by both the "thinking in silos" that tends to accompany sector specialization in policy and research, but also the unequal role that the water, energy and food sectors play in global research and planning (Yillia 2016). Furthermore, the economic value of structural efficiency increases and cost reduction also has a lot of room to expand in the private sector (Ibid).

2.3. THE AFRICAN CONTEXT

Incentives to cut energy demand of municipal water utilities are global. But an analysis of drivers of the energy-for-water dimension bears large potential in Africa specifically for the following reasons:

Firstly, population growth and urbanization rates are extremely high in Africa, with 57.7% of Africans projected to live in urban areas by 2050 – a steep rise from 39.6% in 2011 (UN DESA 2012). This has led to a lag of infrastructure expansion behind demographic change (World Bank 2010). Sub-Saharan Africa is the only region in which the absolute number of people lacking access to electricity is rising and the percentage with access to improved water sources is declining in some countries. In Somalia, only 32% of the population is connected to improved drinking water sources and is ranked the lowest country in the world (World Bank 2016).

Secondly, where large percentages of the population have yet to gain access to improved water sources and sanitation facilities, enhanced cost efficiency enables public services to surpass economic water scarcity and connect communities that are currently deprived. Due to budgetary limits, public services in African developing economies are disproportionally constrained by high operational costs.

Thirdly, where access to improved water supply and sanitation is currently underdeveloped, there is the potential for "leapfrogging". These regions can skip development via resource-intensive infrastructure, which today's developed world previously went through. Countries with gaps in public services can save money by conducting resilient planning consistent with current pressures, and installing modern, efficient and clean technology without having to retrofit existing facilities.

Energy input varies highly in a continent spanning as many climatic zones as Africa. Arid regions in the far North and South are becoming increasingly reliant on seawater desalination as growing demand exacerbates physical water scarcity. The large centre includes tropical regions, where renewable freshwater resources are readily available. However, public services are unable to deliver sufficient clean water to the population due to lack of financial resources or simply underdeveloped infrastructure. WWAP (2014b) refers to this as 'economic water scarcity'. Global Credit Rating Co (Joffe et al. 2008). interprets the comparatively low access rates registered across Africa as a large potential for expansion in the future, something that utilities have to prepare for. The report also indicates that for some utilities the cost for energy only exceeds the sum of water and all other related purchases taken together. The comparison of all cost components individually shows that energy comes in second highest only after staff costs for all utilities listed. Utilities included are located in Kenya, Uganda, Burkina Faso, Senegal and Tunisia, thus covering several climate zones.

The governments of several countries, foremost the United States, the UK, Australia, Spain and South Africa, but also China and the Middle East and North Africa (MENA) region have recognized the value of the water-energy nexus and have funded research programs dedicated to building synergies and achieving energy efficiency in both the water and the energy sectors (e.g. Kenway et al. 2008; Environmental Agency 2008; Yang and Yamazaki 2013; Perrone et al. 2011; Siddiqi and Anadon 2011). South Africa has taken the lead in research on the water-energy nexus in Africa (e.g. Buckley et al. 2011).

The water-scarce MENA region is another frequently studied part of Africa. Siddiqi and Anadon (2011) quantified the water-energy nexus in this area. They concluded that energy generation may be highly water intensive, but water supply cannot function without energy input. They calculated that groundwater pumping accounted for at least 14% of total fuel consumption in Libya. Desalination alone consumes up to 13% of total electricity consumption in Algeria (WWAP 2014b). African countries practicing seawater desalination include Morocco, Algeria, Tunisia, Libya, Egypt and South Africa (FAO 2016). Dubreuil et al. (2013) found that water saving in MENA can reduce electricity consumption by as much as 22% in 2050.

According to Venkatesh et al. (2014), integrated systems analyses to improve energy efficiency in the developing world are scarce due to data limitations. They emphasize that particularly where millions have no access to electricity and cities are rapidly growing, a view on the entire system, beyond individual stages is useful. They emphasize that there is need to assess the external driving forces that may drive up energy demand of water supply systems, in order to find suitable technical solutions.

2.4. PREVIOUS ANALYSES OF SYSTEM DRIVERS

According to Nair et al. (2014), only little research has been carried out to examine underlying drivers and their interactions. Little discussion has been made within the water-energy nexus considering environmental and human impacts on water engineering systems. However, they ultimately determine the input variables to calculate technical parameters, including energy use. Systemic risks threatening the operational energy efficiency of water utilities are linked to hydrology, climate and socio-economic changes (Flörke et al. 2013). Water supply considered as an open system includes a large number of factors contributing to energy intensity. Energy optimization can be seen as a measure to reduce feedback mechanisms within the network of environmental and human-made pressures: On one side, engineered municipal water supply depends on environment, geography and water needs, and on the other side, power generation for energy-using processes contributes to GHG emissions, which alters climate forcing and the hydrological cycle.

Climate is a central driver to energy for water, because it drives the natural water cycle. The IPCC Technical Paper on Climate Change and Water (Bates et al. 2010) states that beyond observed conditions of water infrastructure performance, climate projections should be equally considered in order to prepare for future disruptions caused by climate change. Climate determines water availability for human withdrawal and therefore groundwater dependency, according to Scott (2013). Pumping depth and transport distance are directly affected by climate forcing, leading to changes in energy demands to deliver water, as indicated above. Researchers have linked water use and hydrological models to calculate the volume flow and location of surface water and groundwater sources separately, as done in the WaterGAP (Water Global Assessment and Prognosis) model (Döll et al. 2015).

The previously mentioned TIAM-FR model (Dubreuil et al. 2013), focuses on the impact of different water sources on energy intensity of water supply and wastewater management. However, as previously indicated, kWh/m^3 needed for potable water supply vary significantly even for similar water sources and data on energy consumption of water systems is hardly available, or badly outdated. By examining drivers, infrastructure planners can improve the resilience and efficiencies of their systems by evaluating local sets of structural pressures and feeding this knowledge into scenario calculations with the existing tools mentioned above. Venkatesh et al. (2014) conducted a study examining the impact of climate, geography, socio-economic factors and technology on the energy and carbon intensities of four urban water utilities in different cities. They concluded that the weight of individual drivers varies significantly by case. Respective local conditions must be examined in depth in order to optimize service delivery and the performance of water supply in the future (Ibid). Consistently, a perspective beyond singular drivers is needed to identify all potential systemic risks, followed by a selection made on the basis of their relative gravity in a defined region.

Finally, multiple hydrological sensitivity analyses (e.g. Haddeland et al. 2014; Kiguchi et al. 2015; Flörke et al. 2013) reveal a dominant effect of population scenarios and human behavior on future water availability. Consistently, Reder et al. (2014) found that anthropogenic impacts dominated changes to water quality in Africa, as opposed to natural forces and climate change. Therefore, this study will prioritize human-made drivers to energy intensity.

2.5. SUMMARY

In conclusion to the literature review outlined above, it can be said that energy intensities are highly variable, with a wide spectrum of kWh per cubic meters water delivered to municipal end-users. The strong variation suggests the scope to reduce energy costs both via technical efficiency increases and by targeting the driving forces that influence the input parameters to average electricity requirements. The specific impact depends on local environmental, geographic and socio-economic conditions, which must be identified and examined in order to build robust infrastructure that can withstand current structural trends.

In the developing countries of Africa, cost reduction and energy efficiency optimization bear a triple benefit: (1) public water supply can be expanded to communities currently deprived of access to improved water sources, (2) funds are set free, which can be spent on improving the performance of existing water services, and (3) where the population lacks access to electricity, every kWh saved opens capacity for other much-needed use.

The regions suffering most from environmental and socio-economic pressures are developing countries. Here, meager data availability for water utilities and water quality, let alone water-energy nexus dimensions, makes careful planning very difficult. Particularly in Africa, the analysis of energy intensity of water systems is challenged by huge gaps in available data. Therefore, it is useful to examine driving forces, for which data is available, and derive their impact on the water-energy nexus.

A large set of drivers has been covered by existing research, but only partly related to energy consumption of a municipal water supply chain. What is needed is an approach to quantify environmental and socio-economic drivers that influence the volume of municipal water production as well as the energy intensity per m^3 potable water treated and delivered to end-users. A strong understanding of these drivers will enable to reduce the impact of structural constraints and provide a knowledge base to maximize co-benefits among policy dimensions.

3. Research Objectives

Motivated by the existing knowledge gap, the present study aims to:

(1) identify drivers that affect energy intensity of a municipal water supply chain,

(2) define key indicators to quantify the drivers based on how the drivers interrelate and how they feed into energy intensity calculations, and

(3) determine country-specific sets of risks as well as regional clusters of vulnerability across Africa, based on defined indicators.

The objective of the current study is to provide an analytical tool to determine the impact of anthropogenic factors that drive energy requirements of public water services by undertaking a country assessment for Africa. First, drivers and their interconnection will be identified based on literature followed by an analysis of a selection of key indicators. The quantification of key indicators will serve to examine their relative regional distribution across African countries and determine sets of risks that these countries are facing, supported by a hierarchical cluster analysis to determine similarities and outliers among the cases.

Chapter 4 describes the model in detail, including an outline of the energy-consuming processes along an engineered water supply chain, followed by a review of systemic drivers and their direct or indirect impact on variability of energy use. This chapter will conclude in key indicators derived from the analysis. Chapter 5 presents current baseline conditions, such as the range of operational cost proportions that water utilities in Africa spend on energy. Existing driving forces and their impact on African countries are presented in chapters 6 and 7, respectively. The cluster analysis in chapter 8 determines patterns and outliers among the countries in terms of the impact exerted by the drivers. The discussion of results will conclude the study.

4. Model Description

4.1. SYSTEM BOUNDARIES

Of total "municipal water", an average 58% actually goes to domestic users. Around 12% are used by industry without its own supply and 30% is split evenly between public municipal buildings and services, and commercial users (Sanders and Webber 2012). Similarly, only 1.5% of “drinking water” is really used for drinking (Leclerc et al. 2012). As public water is produced with homogeneous quality and via a single production channel, “municipal”, “domestic” and “drinking” water are often used synonymously. Here they will be used likewise.

The indicators examined in the present study are derived from the following system definition. Figure 1 displays the disaggregated energy use of major processes to provide municipal water to end-users. The object of interest is the amount of energy consumed during operation of a municipal water (MW) supply chain, beginning with water extraction from available sources and ending when the purified water is delivered to end users. Every stage is run by energy-consuming devices, described in chapter 4.2. Their energy requirements depend on a large set of drivers, discussed in chapter 4.3.

The definition of stages is based on the system boundaries of the water supply phase as outlined by a number of studies on energy use of municipal, engineered water supply (e.g. Cooley and Wilkinson 2012; Plappally and Lienhard 2012; Perrone et al. 2011). As displayed below, the municipal water supply chain comprises freshwater extraction, treatment, and distribution to end-users. Energy consumed to heat, cool and pump water within households lies outside the system analysed here, as is wastewater management. Energy intensity of end-use depends on household habits and operational efficiency of water-consuming appliances, which are generally not under the purview of utility operators (Lubega and Farid 2013). Similarly, energy for wastewater management depends on the same household practices resulting in different types and concentrations of pollutants (Plappally and Lienhard 2012).

The diagram below shows the major energy-consuming stages and technical devices employed in typical municipal water utilities. System imports are defined as the recharge of available freshwater sources and seawater. F1, F2 and F3 are the water flows that supply the three freshwater providing processes within the system boundaries. F1, surface water runoff, supplies surface water bodies, such as lakes and rivers. F2, groundwater infiltration, describes the water that permeates the soil layers and recharges renewable groundwater aquifers. Finally, several countries additionally rely on seawater desalination, because their surface and groundwater flows are not sufficient to cover existing freshwater demand.

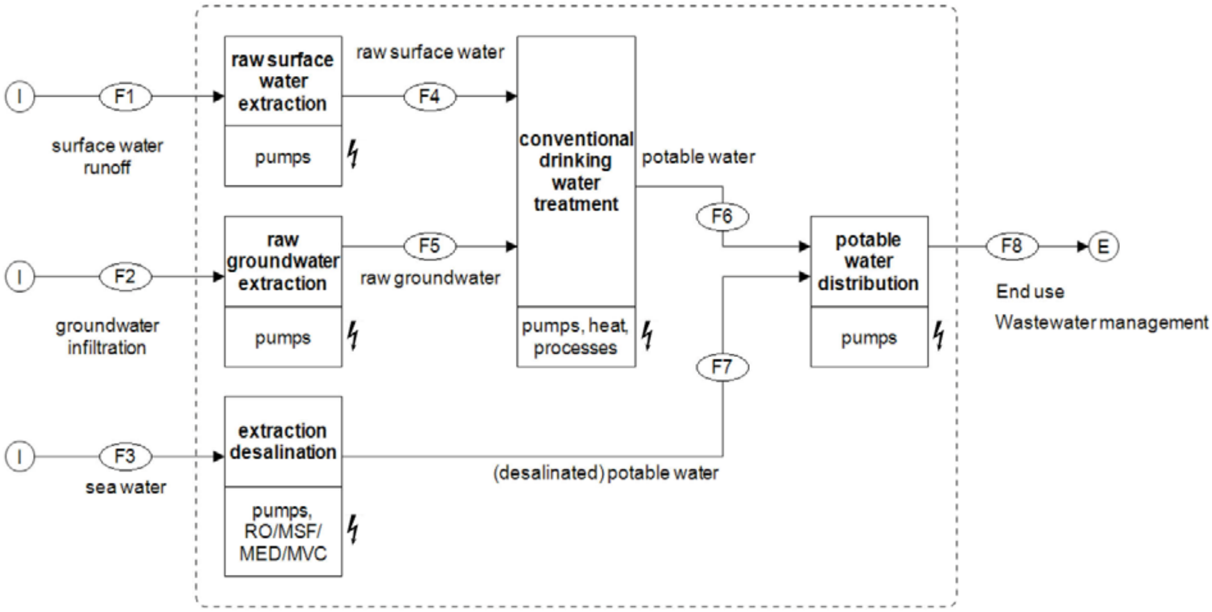

Figure 1: Major energy-consuming stages that comprise a typical municipal water utility. The diagram was designed with STAN (TU Wien 2012).

F3 represents the seawater flow into the municipal water supply system, where it meets the extraction and desalination process. While extracting freshwater from lakes and rivers, or lifting groundwater require only pumps, the process of producing freshwater from seawater additionally requires processes to remove the high mineral content to make it suitable for drinking and other domestic uses. A common mechanical method is Reverse Osmosis (RO). Thermal processes include Multi-stage Flash Distillation (MSF), Multiple Effect Distillation (MED) and Mechanical Vapour Compression (MVC). As sea water withdrawal itself requires virtually no energy (Cooley and Wilkinson 2012) and takes place at the desalination plant, extraction and treatment are taken together as one process.

F4, raw surface water, and F5, raw groundwater, are both transmitted to the conventional treatment process. Pumping as well as heat and other purification processes require electricity to produce F6, potable water, which flows into the municipal transmission lines. There it is mixed with F7, potable water won from desalination. The process of potable water distribution delivers the water to end users and electricity is needed to power pumps. This flow is represented by F9 and exits the system boundaries. Building on above diagram, the next section describes the energy use of the displayed stages in detail.

4.2. ENERGY-CONSUMING PROCESSES

4.2.1. Raw Water Extraction

Groundwater and surface water extraction are very different from each other. However, both essentially require energy for pumping along the entire cycle. It accounts for 90-99% of the total energy usage of a water system (Fishbein 2014). For groundwater, it is needed to vertically transport freshwater from underground reservoirs, while surface water must be delivered from the source water body to the distribution system. In this study, extraction includes conveyance to distribution systems. Freshwater for municipal supply usually passes through treatment facilities somewhere between the point of extraction and where it enters the municipal distribution system. But treatment goes beyond pumping and will be discussed separately. It is very difficult to assess the specific contribution of segments to the overall energy intensity, because transfer lines can consist of several connected pipelines, pumping stations, turbines and canals (Ibid).

To raise well water from subterranean aquifers, both electric submersible pumps and shaft deep well turbine (borehole) pumps are used. Plappally and Lienhard (2012) pinpointed a "*linear relationship (…) between the energy intensity value for ground water pumping and the depth from which it is pumped at a specific pressure.*" They express energy needs for groundwater pumping as follows:

$$E_g = f\,(l,Q,p,t,f_l)$$

where l = distance that the water is lifted, Q = volume of water extracted, p = pressure required at the outlet, and t = pumping duration, f_l = pipe friction, with a constant head. Other authors extend the function by pump and motor efficiency. (e.g. Cooley and Wilkinson 2012) Wells can be drilled very close to where water is needed. Therefore, groundwater requires little to no energy for transport to municipal distribution systems.

Meanwhile, surface water abstraction itself needs no energy, because it is already at the surface (Ibid). A disadvantage is that it must be transported to where it is needed, which accounts for 80-85% of all electricity consumed for surface water supply to distribution systems (Fishbein 2014). Horizontal or vertical centrifugal pumping systems serve surface water transportation, which runs via pipelines, siphons, valves, booster pumping stations, tunnels and aqueducts. Energy requirements of the transport lines primarily vary with the length of the transmission line and elevation changes. As indicated in Table 1 above, energy intensities of extraction and conveyance are location specific. Sometimes, transmission lines need to pump water over mountains, such as in parts of California or water supply to Tijuana in Mexico (Plappally and Lienhard 2012). There are big differences among pumping requirements for plain, varied or hilly terrain. As distance increases, so does the variability in embedded energy. Therefore, reported energy intensities embedded in imported water reveal far higher variability than local surface water (Cooley and Wilkinson 2012). Further, the type of conduit has a large impact. Seepage or percolation through the soil, solar radiation and precipitation impact surface water transportation. Plappally and Lienhard (2012) define functions of energy use for pipeline conveyance as well as for open channels, subjected to atmospheric influences. For surface pipe flows, they express the following:

$$E_{SPF} = f\,(l,Q,A,M,S,t)$$

where l = pipeline length, Q = volume of water transported, A = pipe cross section, M = material-specific constant, S = pipeline slope, and t = pipeline age.

For open flows, they express:

$$E_{SF} = f\,(l,Q,R,k,M,S_c,f_l,T,P_r)$$

where l = channel length with the hydraulic parameter R, k = permeability of the terrain bed, S_c = undulations on the bed, f_l = frictional and vegetative resistance along l, T = evapotranspiration rate, P_r = precipitation rate, Q and M are the same as for pipelines.

4.2.2. Conventional Water Treatment

Municipal water must be treated to comply with physical and chemical quality requirements, as defined by the World Health Organisation (WHO) or governmental agencies. The WHO guidelines are not mandatory, but represent a worldwide reference point for standard-setting and legislation. They define concentrations for a host of substances below which safe drinking water quality is ensured. The guidelines include microbial, chemical and radiological hazards, as well as recommendations for taste, odour and appearance for acceptability. These include standards for hardness, turbidity, metals, TDS and dissolved O_2 content, among others (WHO 2011).

Conventional drinking water treatment is made up of coagulation, sedimentation, filtration and disinfection (Cooley and Wilkinson 2012). Essentially, the relevant processes can be divided into chemical treatment and physical treatment. Chemical treatment aims at disinfection and clarification. Piston-type dosing pumps account for the bulk of energy consumption. Physical treatment through filtration and sedimentation needs pumps, fans, agitators and centrifugal blowers (Barry 2007). Further, a groundwater treatment plant may have a pumping system, disinfection tank, a storage tank and a booster pump. Lubega and Farid (2013) find that pumping accounts for 98% of energy demand of groundwater extraction and treatment combined.

Deep well water (at less than 300m depth) is generally considered microbial-free and usually requires only basic purification through chlorination (Fishbein 2014). However, it may contain inorganic minerals from natural geological formation. This can set free iron, manganese, arsenic, radionuclides, dissolved gases, inorganic and organic chemicals and in some cases even micro-organisms. If underground aquifers interact with surface water flow, they are exposed to microbial contamination from agricultural sources and human waste, as well as chemicals from industrial discharges (Plappally and Lienhard 2012). The injection of chlorine gas or chlorine-containing salts consumes very little energy compared to ozonation or UV irradiation in the case of microbial contamination, or aeration, ozonation and membrane treatment to remove industrial chemicals. Aeration removes dissolved gases, oxidation and filtration remove metals, while softening removes calcium and magnesium ions.

Surface water is directly exposed to the atmosphere and waste from humans, animals and vegetation. These processes cause turbidity and impurities, such as silt, algae, micro-organisms, biological contaminants, larger suspended particles such as plant material and man-made compounds, such as pharmaceuticals and petrochemicals. According to the size of pollutants, treatment units include mechanical screens, sedimentation or flocculation tanks, multiple filtration media and disinfection tanks. Chemical contaminants require additional purification.

During sedimentation, energy is expended to maintain a low flow velocity that enables large particles to settle to the bottom of the tank. This results in an average energy use of about $5x10^{-4}$ – $1x10^{-3}$ kWh/m^3 (Ibid). As smaller particles remain suspended, coagulants and flocculation aids are added to cause them to agglomerate. Agitators promote mixing, consuming around 0.4 – 0.7 kWh/m^3. Chemicals are used for many purposes in water treatment: Besides ozonation, coagulation and disinfection, chemicals are added for softening, carbonation, pH adjustment and to prevent excessive softening and calcium precipitation. Flocculation for high rate clarification uses aiding polymers and micro-sand. Mechanised impellers, static mixing elements, or nozzle injector-driven diaphragm pumps are applied to promote dispersion (Hammer and Hammer 2008). Besides, the production of required chemicals is in itself energy-intensive (Plappally and Lienhard 2012). Flocculation and removal of dissolved gases is done by dissolved air flotation, where a pressurised stream of clarified effluent is supersaturated with air, producing bubbles. About 9.5×10^{-3} – 35.5×10^{-3} kWh/m^3 are required to balance pressure differences (Goldstein and Smith 2002).

Filtration removes persisting impurities as the water passes through a porous granular media filter. Finally, disinfection techniques free the water from bacteria and other pathogens. Ozonation additionally oxidizes compounds that cause bad taste and odour. As O_3 is an unstable gas, it must be produced from pure oxygen on site. It is fed between two electrodes at high voltage consuming around 0.2 kWh/m^3. (WEF 2010) UV radiation is an alternative disinfection method. Depending on the volume of water processed, low or medium-pressure lamps are applied to disable the reproduction of micro-organisms (Cooley and Wilkinson 2012). Bacteria and viruses are also removed by low-pressure membrane techniques, such as microfiltration and ultrafiltration. These techniques remove turbidity and do not produce by-products (Plappally and Lienhard 2012). Besides contamination characteristics, the age and efficiency of the equipment for drinking water purification contributes to variations of energy intensities measured for treatment plants (Venkatesh et al. 2014). The size, i.e. plant capacity, determines kWh/m^3 energy costs for purification, which decrease with increasing scale (Yang and Yamazaki 2013). Finally, not only process equipment demands energy, but also building services, the production of input substances and treatment waste disposal.

4.2.3. Desalination

Similar to surface water, energy use to extract seawater is almost zero. However, for desalination, energy is the largest single cost (Cooley and Wilkinson 2012). Energy requirements depend on total dissolved solid (TDS) content and on the type of technology employed to remove it. As mentioned previously, there are two major methods to reduce mineral and salt content in seawater and brackish water: thermal and mechanical. Thermal (distillation) processes include MSF, MED and MVC. Mechanical methods, such as RO, nanofiltration and electrodialysis, apply pressure or electric fields to send water through membranes and remove ions.

The energy intensity of mechanical desalination varies with TDS content, while for thermal processes it is independent of mineral solute concentrations. Taken together, thermal methods are most common, while RO is the single most common method. RO applies pressure across the semi-permeable membrane, which must be larger than the natural osmotic pressure (Lubega and Farid 2013). It is usually more efficient than thermal techniques, particularly for brackish water, where 500ppm, 1000ppm and 4000ppm TDS draw 0.66, 0.79 and 1.59 kWh/m^3, respectively. Seawater desalination via RO uses around 2.5 – 7 kWh/m^3 (Plappally and Lienhard 2012). To compare, the energy costs of MSF seawater desalination are at 10-20 kWh/m^3 (Sommariva 2010).

Energy sources are particularly relevant at this stage. Almost all thermal processes draw low temperature steam from neighbouring power plants, while mechanical desalination uses electricity. Desalination is very energy-intensive, but compared to transporting water across large distances or pumping from further depths, it may be feasible considering both finances and energy use (Plappally and Lienhard 2012; Cooley and Wilkinson 2012).

4.2.4. Potable Water Distribution

Municipal distribution grids stand under high pressure. Therefore, treatment plants install booster pumps to meet the pressure requirements for distribution to domestic and commercial end users. In fact, Arpke and Hutzler (2006) found that booster pumping is equivalent to 85% of total energy consumption in conventional water treatment plants. However, economies of scale are at work with additional volume of water pumped (Plappally and Lienhard 2012). Horizontal or vertical centrifugal pumping stations increase the pressure of water going into distribution networks. They are used when introducing water to the distribution network from conveyance systems or treatment facilities, and for pumping water up a positive elevation change (Barry 2007).

Exploiting gravity pressurisation can reduce energy intensity, but it rises with age or poor maintenance of the distribution system. Further, as the necessary pipeline length increases, so does the energy consumed during their installation and, earlier, for the production of construction materials (Venkatesh et al. 2014). According to a survey of water utilities in the US (AwwaRF 2007), 78% of variance in energy use at the distribution stage is determined by flow, distribution pump horsepower, elevation changes and the presence or absence of lagoon dewatering, pressure filtration and residual gravity thickening.

The amount of water for domestic use that is lost through leakages during transportation further exacerbates energy costs. More than 30% is lost on average from water distribution systems in Africa, according to the International Benchmarking Network for Water and Sanitation Utilities (IBNET 2015). From there it either meets groundwater through infiltration or evaporates to the atmosphere. This is one of many structural drivers of energy intensity along the municipal water supply chain. These are discussed in their entirety in the next section. Chapter 4.3 identifies drivers that impact energy intensity at the individual stages specified above.

4.3. SYSTEM DRIVERS

Concluding from the previous discussion of energy-using processes, it can be said that energy intensity essentially depends on the (1) volume of drinking water produced and (2) factors that influence energy consumption (kWh) per unit water supplied (m^3).

(1) *Volume of MW produced:* Energy intensity depends on how much water is processed by the facilities of the supply chain, which are necessary to deliver freshwater to end users at the required quality to ensure human health.

(2) *Unit energy efficiency:* The amount of energy needed to process and deliver one cubic metre of water for potable use depends on:

   a. *Available freshwater sources*: Per unit energy intensity (kWh/m^3) of freshwater extraction depends on the type and volume of freshwater sources available to meet municipal water demand.

   b. *Raw water quality:* The energy intensity at the treatment stage depends on the type and concentration of contaminants present in raw water.

c. *Pumping requirements:* The energy use of pumps for conveyance and urban distribution depends on variable pressure requirements, defined by distance and slope.

It must be noted that above classification does not indicate non-linear kWh/m^3 requirements that accompany an increase in volume, such as economies of scale. But as the relationship of energy use to larger volume of water is always positive, the slope will not be considered for the purpose of this study.

This leads to the classification of the following system drivers:

For (1), *drivers of MW demand:* As utilities produce the volume that is required by end users, the amount of water that must pass through the system depends on drivers of municipal demand. This is equivalent to the system exports in figure 1.

For (2), a series of *supply-side drivers*, namely:

a. *Drivers of freshwater supply for MW use:* The system imports represent the recharge of available freshwater sources, which are limited. Location, type and size of readily available freshwater depend on drivers of freshwater recharge and abstraction by competing uses.

b. *Drivers of water quality:* The type and concentration of pollutants in freshwater sources that are accessed for municipal use depends on point and diffuse sources of human, agricultural and industrial waste.

c. *Drivers of pumping requirements:* Variable pressure requirements depend on the distance and terrain connecting freshwater reserves to end users, as well as the length of the municipal distribution network and associated water losses.

Supply-side drivers influence the conditions that determine per unit energy input, while *demand-side drivers* decide the volume of water produced by the system. Cumulative energy demand rises linearly with volume, except for that of treatment process, where economics of scale are at work (see chapter 4.2.2). The following section will elaborate the sub-systems that influence water supply characteristics and MW demand.

4.3.1. Supply-Side Drivers

4.3.1.1. Drivers of Freshwater Supply for Municipal Water Use

Besides pump and motor efficiencies, per unit energy intensities of extraction depend on the location, type and size of available freshwater reserves in the form of lakes, rivers, wetlands, groundwater aquifers and other reservoirs. This chapter will include environmental drivers, in order to discuss how these forces interact with human activity.

Drivers of the hydrological cycle

Ambient temperature, wind speed, specific humidity, atmospheric pressure and net radiation determine climate forcing, which influences freshwater recharge rates via precipitation and potential evapotranspiration. Biophysical exchange drivers determine the actual evapotranspiration rate and effective precipitation, i.e. throughfall (Alcamo et al. 2007; Iofin 2015). These include vegetation and capillary rise, absorptive and infiltration capacity of the soil, hydraulic conductivity of the subsoil, as well as topography. They finally determine the total runoff from land along with the fraction of fast surface water runoff and infiltration, or slow subsurface runoff (Döll et al. 2014). Snowfall and excess infiltration from irrigation are further sources of freshwater. Natural storage capacity dampens inter-annual variability of precipitation, which is strongest in the sub-tropics.

Anthropogenic impacts on environmental drivers

Humans influence the hydrological cycle in many ways, most prominently through climate change and the exponential growth of water use in the last decades. This includes the average ambient temperature rise induced by excessive anthropogenic greenhouse gas (GHG) emissions. According to the IPCC Fourth Assessment Report (IPCC 2007), global variability of longitudinally averaged precipitation will be amplified by climate change. A certain level of base-flow is necessary to sustain ecosystems and prolonged drought conditions deplete freshwater reserves beyond their average annual minimum flow. This way, drought destroys land cover and soil texture, which are critical to local water storage (USAID 2015). Similar alterations occur from direct land use change for human settlements or production. Meanwhile, excessive groundwater pumping and sea level rise have led to salt water intrusion into groundwater bodies in coastal proximity. However, researchers assume that there is a dampening effect of anthropogenic CO_2 emissions, as plant physiological response to higher atmospheric concentrations increases runoff (e.g. Betts et al. 2007).

The construction of dams and water towers for storage capacity helps to capture precipitation during heavy rain fall periods, but open-air basins are subject to evaporation losses, as mentioned above. Inter-basin transfers are often extremely energy-intensive. In some cases seawater desalination is a cheaper alternative in water scarce areas (Cooley and Wilkinson 2012). Freshwater bodies often transcend national borders, calling to incorporate upstream abstraction into domestic planning.

Competing interests

The agricultural and industrial sectors compete for freshwater with municipal demand. Not all use is consumptive. A large fraction is returned to water bodies by all three sectors via wastewater. But this may be far from the source of extraction and usually it is not fit for direct reuse. Thus, socio-economic and technological development has led to a strong increase in withdrawal and consumption (Wada et al. 2014).

The increase of agricultural withdrawal is due to a rise in food demand. This has caused rising withdrawal to support livestock and crop-specific irrigation needs. Today, agriculture accounts for some 70% of total water withdrawal globally (Leclerc et al. 2012). In water use models, paddy and non-paddy crops as well as livestock farming are distinguished due to highly diverging water intensity (e.g. Döll et al. 2012). Livestock densities are a common indicator for agricultural water withdrawal (e.g. Alcamo et al. 2007) and livestock water demand varies with daily air temperature (Wada et al. 2010). Virtual water trade may significantly pressure economies with a strong primary sector (Padowski et al. 2015). Meanwhile, yield-enhancing technologies may lead to reduced water needs for food, feed and biofuel cultivation.

The industry sector comprises power generation and manufacturing. The share of water-intensive industries, such as mining or fuel production, textiles, metallurgy, and paper industries, contributes to structural water intensity (Grady et al. 2014; Leclerc et al. 2012). Alcamo et al. (2003) differentiate between thermal and hydroelectric plant capacity to capture the diverging fraction of consumptive water use. Dziegielewski et al. (2002) found that manufacturing gross value added (GVA) is positively correlated with water withdrawals for this sector. But water intensity does not necessarily have a linear link to industrial output. Particularly in countries at an early development stage, "skipping" intermediate technology through "leapfrogging" in both electricity generation and manufacturing bears huge potential, as mentioned in chapter 2.2. Kiguchi et al. (2015) identify national electricity production as the main driver of industrial water use due to its proportion within the GDP share of industry. They set water consumption intensity by the energy sector as an indicator for the overall improvement of industrial water use efficiency. Alcamo et al. (2003) also emphasize the weight of electricity generation and project structural water intensity as decreasing sharply with economic development at first and leveling as GDP/capita rises. Additionally to water recycling for irrigation, gray water is also largely reused in industry (Dubreuil et al. 2013).

Institutional setting

Institutional factors that influence the allocation of freshwater reserves include government corruption and the capacity of existing governance mechanisms to manage water. The regulation and monitoring of water quantity and quality as well as the effectiveness of implementation are part of this (Padowski et al. 2015).

4.3.1.2. Drivers of Water Quality

There are a series of environmental factors, which influence water quality such as water temperature, extreme precipitation, i.e. flooding, coastal proximity and naturally occurring organic and inorganic substances (Voß et al. 2012). Henceforth, human impacts are discussed in detail. Pollutants are discharged from point and diffuse sources. Also upstream pollution deserves attention as it leads to a deteriorated inflow quality in some countries (Padowski et al. 2015).

Point sources

Point sources comprise domestic sewage, industrial wastewater discharge and urban surface runoff (Reder et al. 2014). Urbanization is broadly understood to reduce regional water quality due to a dense occurrence of these factors (e.g. Sood and Smakhtin 2014; Grady et al. 2014; Yillia 2016). Industrial production tends to eject pollutants beyond microbial impurities, which creates the need for more energy-intensive treatment processes such as aeration, ozonation, and membrane treatment (Plappally and Lienhard 2012). As heavy-polluting industries are transferred from high-income to low-income countries with lenient effluent treatment frameworks, the latter countries face a double burden with limited economic capacity and equipment to treat industrial waste (Leclerc et al. 2012). Pollution through human waste is reduced with increased access to improved sanitation facilities (Sood and Smakhtin 2014), but notably only if wastewater treatment is in place (Reder et al. 2014).

Diffuse sources

Diffuse sources include nutrient-rich infiltration from excess irrigation water, organic and industrial fertilizers, as well as geogenic background sources. Manure application and domestic sewage are sources of faecal coliform (FC) and oxygen-depleting microorganisms. Scattered settlements also work as diffuse sources when they lack improved human waste disposal systems (Ibid; Voß et al. 2012). Reder et al. (2014) modelled water pollution across the African continent and found that pollution hotspots were located in regions with high population density and increased human activities. Pollutant concentrations are subject to dilution, which varies with the volumetric flow of the polluted water body. In locations with high seasonal variation, water quality equally varies (Yang and Yamazaki 2013).

Institutional setting

Similar to allocation of freshwater sources, water quality is also influenced by the institutional setting. Specifically, the stringency of regulations (Cooley and Wilkinson 2012), the ability to pay for effluent treatment (Grady et al. 2014), the awareness or willingness to pay (Francis et al. 2015) for water treatment impact receiving water quality. They may be affected by corruption and lack of education.

4.3.1.3. Drivers of Pumping Requirements

Drivers of kWh electricity use per m^3 drinking water pumped to end-users depends on elevation change, or as Yang and Yamazaki (2013) define, on flat, moderate, or hilly terrain, and on pumping distance. Here, the challenge is to maintain a constant pressure in the distribution network. However, per unit energy costs depend most significantly on the potential for gravity pressurization. Urban sprawl extends the piping distance

(Venkatesh et al. 2014). Both topography and urban sprawl cannot be meaningfully examined at a national level. Therefore, they will not be further analysed here.

4.3.2. Demand-side Drivers

A host of demographic conditions influence municipal water demand, including population growth, the fraction of urban population and the urbanization rate (Leclerc et al. 2012; Sood and Smakhtin 2014; Padowksi et al. 2015). Urban areas are rapidly expanding, projected to hold 70% of the global population by 2050, according to WWAP (2014b). Per capita consumption patterns vary with average per capita income, but water use levels out with the rate of improvement in water use efficiency of domestic appliances and activities (Alcamo et al. 2003; Wada et al. 2014). Several studies use the GINI coefficient to measure equity of water use (e.g. Cullis and van Koppen 2007) and water pollution distribution (e.g. Chen et al. 2012). Hot and arid climatic conditions elevate household water consumption (Wada et al. 2014).

The average water intensity of urban households increases as coverage of safe drinking water connections expands. It grows further as more households gain access to sanitation facilities as water use tends to increase with proximity to the water source (Plappally and Lienhard 2012; Flörke et al. 2013). According to Leclerc et al. (2012), "*regions where water resources are the least exploited are those where access to water is least developed*". Additionally, where coverage with water and sanitation connections is very low, there is a high growth potential for water utilities in these areas. But it depends on national socio-economic conditions, whether infrastructure can be developed or the fraction of population with access to public water services remains low (Joffe et al. 2008). Finally, infrastructure maintenance influences volume of non-revenue water. Losses from leaking pipes and taps increase the volume of drinking water that must be produced and delivered to end-users. In Africa, water utilities have to overshoot demand at around 30% to compensate leakages (IBNET 2015).

4.3.3. Interdependencies among Identified Drivers

Figure 2 (next page) illustrates how supply and demand drivers feed into the key conditions that influence energy consumption and how they interact with each other. Each arrow represents an impact, elaborated in table 2. The symbols ⊕ and ⊖

indicate how changes in one driver result in either an increase (positive feedback) or a decrease (negative feedback) of the intensity of another driver.

Table 2: Interactions between the system drivers as enumerated in figure 2. (Cont. p30)

1a	Precipitation brings water from the atmosphere back to the earth. Renewable recharge is refilled by precipitation.	**6a**	Water abstraction by competing interests, namely the industrial sector, which comprises manufacturing and energy, and agriculture, reduces the volume of MW.
1b	Evapotranspiration reduces available water from open air basins such as rivers and lakes and other water bodies that are in contact with the atmosphere.	**6b**	Competing interests also negatively impact water quality as fertilizers, pesticides, metals, and other organic and inorganic substances enter water bodies. Excess water from irrigation cannot be treated as it seeps through the soil to groundwater. Factories and power stations can install end-of-pipe technologies for effluent treatment. Even then, discharges adversely affect receiving water.
2a	Biophysical exchange drivers comprise land cover, soil type and topography. Together, they determine how much of the water gained from precipitation is transpired by vegetation, evaporates from the surface, infiltrates to underground aquifers, or runs into surface water bodies. Local conditions can be favorable or unfavorable to the extent of exploitable water resources.	**7**	As economies develop, water intensities of manufacturing and energy generation decrease, because producers install modern technology and their product mix tends to transform into less water-intensive goods.
2b	Topography influences pumping requirements at the conveyance and distribution stages of an engineered water supply system.	**8**	Wastewater reuse decreases the volume of withdrawal by competing sectors. Municipal wastewater recycling is very cost-intensive and is hardly practiced.
3	Renewable recharge, with its characteristics resulting from mentioned conditions, determines the type and size of FW reserves.	**9a**	Population growth increases withdrawal by industry and agriculture as demand for food, manufactured goods and energy rise.
4	Temperature increases due to climate change are projected to either increase or decrease the climate forces, precipitation and evapotranspiration, depending on the geographic position.	**9b**	Population growth increases population density (inhabitant/km^2).
5	Storage capacity increases the size of freshwater reserves as it increases the available volume during arid periods.	**9c**	Population growth in urban areas – a product of absolute population growth and urbanization – increases the area consumed by municipalities, or urban sprawl.

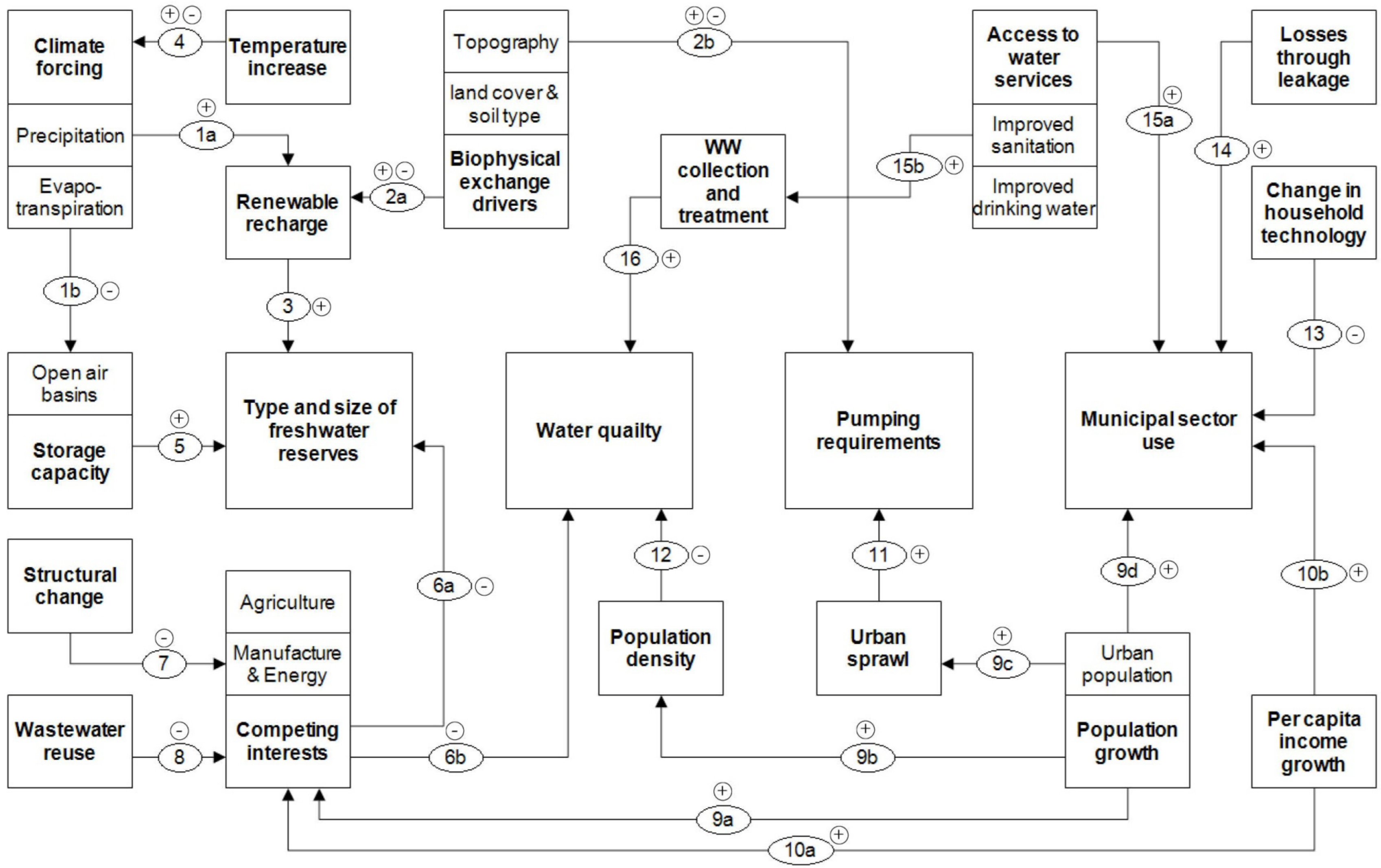

Figure 2: Interdependency of environmental and socio-economic drivers as well as influence on energy consumption of water utilities. Designed with STAN. (TU Wien 2012)

Table 2, cont.

9d	Urban population growth increases the volume of MW use.	**13**	Change in household technology reduces the burden on resources from per capita income growth. Rising living standards tend to improve domestic water use efficiency.
10a	Per capita income growth increases the water needs of the productive sectors as per capita demand for goods rises with domestic budgets. Population growth and per capita income growth impute the effect of GDP growth on competing sector withdrawal.	**14**	Losses through leakage occur during water transport, but impact MW demand. Water utilities have to overshoot revenue water demand to compensate for leakages.
10b	Per capita income growth increases municipal sector use as living standards increase.	**15a**	Access to water services, i.e. improved drinking water and sanitation, increases municipal sector use as clean water becomes more easily accessible.
11	Urban sprawl increases pumping requirements as piping distance expand and pressure maintenance is challenged.	**15b**	Providing access to improved sanitation system means that wastewater management is expanded.
12	Population density adversely impacts water quality as human activity and corresponding pollution becomes denser. This puts additional pressure on environmental regeneration capacity.	**16**	If municipal wastewater collection and treatment is expanded, this improves water quality, or at least dampens the adverse effect of population density.

4.4. KEY INDICATORS

This chapter translates the interconnections between drivers and parameters determining energy use (figure 2) into a set of key indicators, quantified for 52 African countries. Almost all country-level data needed was found available for this number and for 2014. Exceptions will be pointed out, for which the latest available value was used, none earlier than 2005. All variables and corresponding years are listed in Annex 1.

4.4.1. Indicators of Baseline Conditions

Table 3: Key indicators that determine current energy intensity in municipal water supply.

Cost of electricity as a fraction of total operational costs (%)	
E-COST%	indicates the proportion of electricity costs to total operational costs as reported by water utilities and provided by IBNET (2015). Data for kWh/m^3 is hardly available, nor are electricity prices for the given countries and years with which to calculate per unit energy use[1]. Mean values are used, where several utilities operate in a country.

[1] For the required countries and time periods, electricity prices were unavailable as searched in the World Bank, OECD/IEA and several regional databases.

Total annual renewable freshwater (FW) resources per inhabitant (m^3/capita)	
TOTRENCAP	points to water scarcity and water abundance. According to the Falkenmark Index, countries are water scarce, if total annual renewable freshwater resources per capita amount to less than 1000m^3/inhabitant. This is enough to cover physiological needs, but not food production. Water stress occurs with less than 1700m^3/inhabitant per year. There, water shortages may be expected. (White 2012) This indicator disregards inter-annual variability and the actually exploitable fraction. A certain baseflow is needed to sustain ecosystems and some freshwater is not accessible. But data on "exploitable sources", as defined by FAO, is available only for 12 African countries, so total renewable resources provides the reference point. Data is provided by the AQUASTAT database of the UN Food and Agriculture Organisation (FAO 2016).
Annual MW withdrawal (10^9m^3)	
MUNWD	quantifies current demand. Values were calculated with World Bank (2016) data for [*annual freshwater withdrawals, domestic (% of total freshwater withdrawals)*] * [*total annual freshwater withdrawals (10^9m^3)*].
Total annual abstraction over total annual renewable FW (%)	
TOTABST/ TOTREN	relates total abstraction to available resources. It is calculated using data for total freshwater abstraction (World Bank 2016) and total annual renewable freshwater resources (FAO 2016).
Relative source dependency: surface water over groundwater (scalar fraction)	
SWGWDEP	approximates the amount of surface water and groundwater withdrawn within a country, i.e. the relative dependency on the type of freshwater source. This is a useful value due to lack of data on actual annual abstractions by source for African countries. This is calculated as [*total renewable surface water (10^9m^3/year)*] / [*total renewable groundwater (10^9m^3/year)*] with data from FAO (2016). Additionally, the Natural Environment Research Council (NERC) published a map of estimated groundwater levels across Africa. (MacDonald and Bonsor 2011) Grid, or country data are not provided, but the colour-coded image will support the analysis. As mentioned in section 4.2.2, the relative source dependency plays a significant role for both extraction and treatment requirements.

4.4.2. Key indicators – Raw Water Extraction

Table 4: Key indicators to quantify anthropogenic impacts on freshwater availability for municipal use

Annual FW withdrawal by agriculture as a fraction of total withdrawal (%)	
ABSTAGRI	approximates the weight of the agricultural sector on water resources relative to industry and municipal abstraction. Data for all variables in this table are taken from the World Bank database (2016).

Annual FW withdrawal by industry as a fraction of total withdrawal (%)	
ABSTIND	represents the relative weight posed by the industrial sector, i.e. energy and manufacture.
Annual growth rate of agricultural value added (%)	
VAAGRIGROW	The approximation of agricultural production via value added (VA) is more accurate than total productive output as it is a net value. VA is calculated as ∑*(outputs)* - ∑*(intermediate inputs)* and is based on constant local currency. Data for VAAGRIGROW and VAINDGROW are available for 46 countries.
Annual growth rate of industrial VA (%)	
VAINDGROW	is the approximation of industrial production increase.

Average per capita income growth as a driver of freshwater withdrawal by competing sectors is captured by VA growth of the two major competing sectors. Examining demand increase additionally could distort the picture, because demand can be met with imports, which are excluded from VA by definition. This way only domestic production is taken into account. Further, seasonal variability is out of scope, as this study focuses on human made drivers. This also excludes storage capacity as a response to precipitation patterns.

4.4.3. Key indicators – Drinking Water Treatment

Table 5: Key indicators to quantify drivers of water quality

Annual population growth (%)	
POPGROW	For drivers of FW sources, the effect of population growth on competing sectors is captured by value added growth of agriculture and industry. Here, it is relevant as it drives population density.
Population density (people/km^2 of land area)	
POPDENSE	Population density can be misleading when analysed on country level, because subnational variations are invisible. For example in the arid South Mediterranean countries, populations and the major human activity take place in densely populated areas along the northern coastline. To select the variable that corresponds most accurately to pollution levels, several indicators were compared to the regional distribution of pollution across Africa as modelled by Reder et al. (2014). Among values for number of people living in agglomerations larger than 1M, the same in % and average population density per km^2, the latter coincided most with modelled contamination levels (see section 6.1.2).

Population with access to improved sanitation facilities (%)	
ACCSAN	is the population with access as a fraction of total population, which indicates the extent of wastewater *collection* in a country. The latest available value of Somalia is for 2011. If sanitation infrastructure covers a small portion of the population, it is expected to grow in the future, depending on economic development.
Portion of wastewater that is treated (%)	
WWTREAT	Reder et al. (2014) found that increased coverage with sanitation facilities only improves water quality if wastewater treatment is in place. This variable indicates treatment *levels*.
Pollution by agriculture and industry	
ABSTAGRI, ABSTIND, VAAGRIGROW, VAINDGROW	Seepage from excess irrigation and industrial wastewater may heavily pollute groundwater and surface water bodies, especially in developing countries, where regulations are lenient and end-of-pipe technologies are rare.

All indicators in the table above are quantified with World Bank (2016) data for the year 2014, except population density in South Sudan, which is taken from The World Factbook (CIA 2016), and the fraction of wastewater treatment. The latter is provided by YSELP and CIESIN (2014) for all countries, except Comoros, Somalia and South Sudan. According to UNEP (2004), wastewater management in Comoros is very similar to conditions in Madagascar, Mauritius and the Seychelles. Therefore, the value for Comoros is calculated as the mean of the three countries. FAO (2016) provides a value for Somalia in 2003 and South Sudan receives the same value as Sudan.

4.4.4. Key indicators – Volume of Municipal Water Produced

Table 6: Key indicators to quantify drivers of municipal water demand

Annual urban population growth (%)	
URBPOPGROW	represents the pressure on the expansion of public services. Data for **r, s, t** and **u** are World Bank data (World Bank 2016).
Annual municipal withdrawal per urban inhabitant (m^3/cap)	
MUNWD/URBPOP	indicates how steep municipal demand will rise with per capita income growth. Where per capita MW use is low, it can be expected to rise with economic development in the future. As it rises, eventually households become saturated with water-using appliances and habits assimilate to levels in developed countries, leading to a stabilisation of per capita MW demand (Alcamo et al. 2003). Therefore, if this value lies far below the developed country mean, demand will increase sharply with economic development. The 2014 OECD mean lies at 155.04 m^3/urban inhabitant (World Bank 2016).

Population with access to improved water sources (%)	
ACCIWS	If the coverage with access to improved water sources is very low, there is large potential for the expansion of public services in the future, which in turn will drive up per capita MW demand. As previously mentioned, this depends on economic development. The latest value for Somalia is from 2011.
Non-revenue water as a fraction of total MW produced (%)	
LOSSES%	measures the fraction of non-revenue water, or distribution losses, as its relative contribution to total municipal withdrawal. Latest available values were used as provided by IBNET (2015) for 36 countries. The data represent national averages of measurements reported by utilities, the earliest for 2005.
Annual average per capita income growth (%)	
GDPCAPGROW	measures economic capacity for services expansion. Data for Angola was taken from Trading Economics (2016).

Due to lack of data, water recycling and industrial wastewater treatment will not be considered. The dilution effect, which refers to reduced pressure of concentrations with higher volumes of receiving water, will not be considered either, as this depends on micro-level conditions. Similarly, topography and urban sprawl cannot be captured on national scale, which excludes drivers of energy intensity in pumping needs at the distribution stage. Having presented the indicators, the next chapter will present reported costs of electricity as a baseline as well as characteristics of current water supply, water quality and municipal water demand.

5. Current Conditions

5.1. COST OF ELECTRICITY FOR PUBLIC WATER SUPPLY

The amount of money water utilities spend on electricity varies highly across Africa. Figure 3 illustrates the regional variance among average operational cost splits for electricity as percent of total operational costs in African countries with available data. Proportions range from 1.40% in Namibia to 39.50% in Senegal. The map illustrates that there is no relation to water poor or water abundant zones. Arid regions in the south, such as South Africa and Namibia spend a small proportion of operational costs on electricity, while countries at central latitudes, such as Liberia, Ghana, Benin, and especially Cameroon and Gabon spend much more.

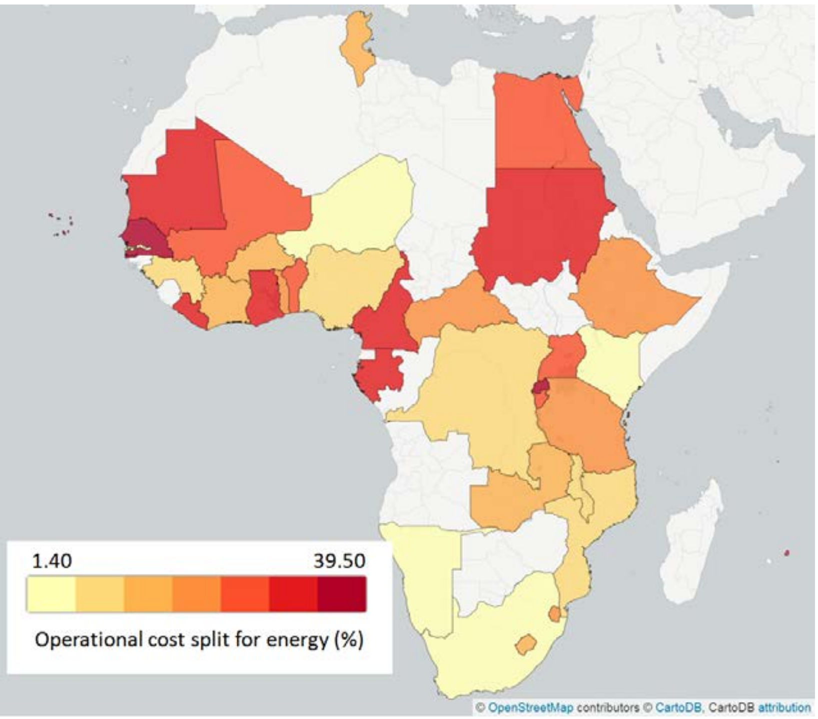

Figure 3: Country-level average expenditure on electricity as % of total operational costs of water utilities (E-COST%). Grey marks the countries, where no data is available. All maps presented in this study are visualised with Jenks breaks, which minimise variance within groups and maximises distance between groups.

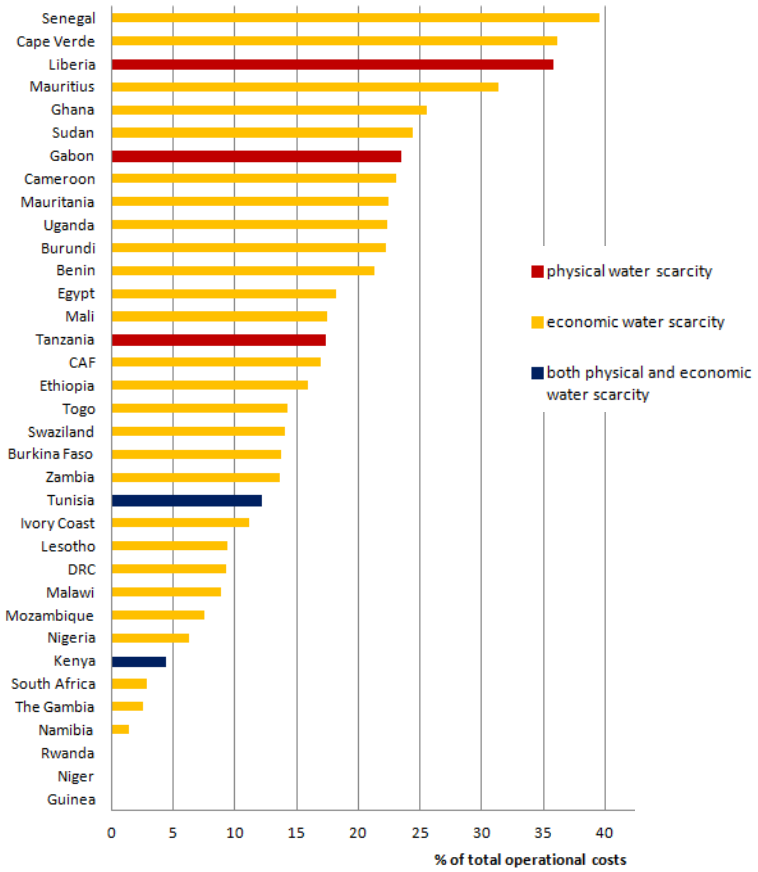

Figure 4: Countries by average cost of electricity as % of total operational costs. Data: IBNET (2015)

In figure 4, the bar graph on the left side orders the countries with available data by their E-COST% values. Bars in red indicate physical water scarcity in these countries, i.e. only 1,000m^3 annual renewable freshwater resources per capita. This covers only physiological needs for drinking, basic hygiene and cooking, but does not last for productive uses such as irrigation or livestock farming. Orange marks countries that face economic water scarcity, where resources are sufficient to cover environmental and human needs, but malnutrition still exists due to human, institutional and financial limitations to properly manage water supply (IWMI 2007). Here, planning and cost optimisation can go long ways to improve the wellbeing of inhabitants. Dark blue colour points to countries that face both physical and economic water scarcity. The colour code shows that physical water scarcity does not necessarily mean disproportionate electricity costs. This can be due to factors contributing to energy intensity of extraction, transport and treatment, or low expenditure on wages and other equipment. Annex 2 provides all numeric values and a bar graph with countries ranked by per costs spent on electricity per unit municipal water produced (USD/1,000m^3), to control for potential distortion of E-COST% by other cost-intensive inputs during water supply operations.

5.2. FRESHWATER SUPPLY

5.2.1. Resource Abundance and Resource Scarcity

Physical water scarcity can do much to drive up electricity use for domestic water supply. Figure 5 illustrates the regional distribution of total renewable freshwater resources per capita, ranking from 112m^3 per person per annum in Libya to 180,000m^3 in Congo. The bubble areas add the parameter of population growth. Countries coloured in beige and green are arid and semi-arid regions, while water availability increases towards the central tropical regions. The top five water abundant countries are the Central African Republic (28,800m^3), Equatorial Guinea (30,800m^3), Liberia (51,500m^3), Gabon (96,200m^3) and Congo (180,000m^3). Countries with large bubbles in areas with water scarcity or periodic shortages bear the largest weight of demographic change as already scarce resources will have to serve growing demand for drinking water and the production of food, goods and energy. Dark coloured countries with small population growth are hardly threatened.

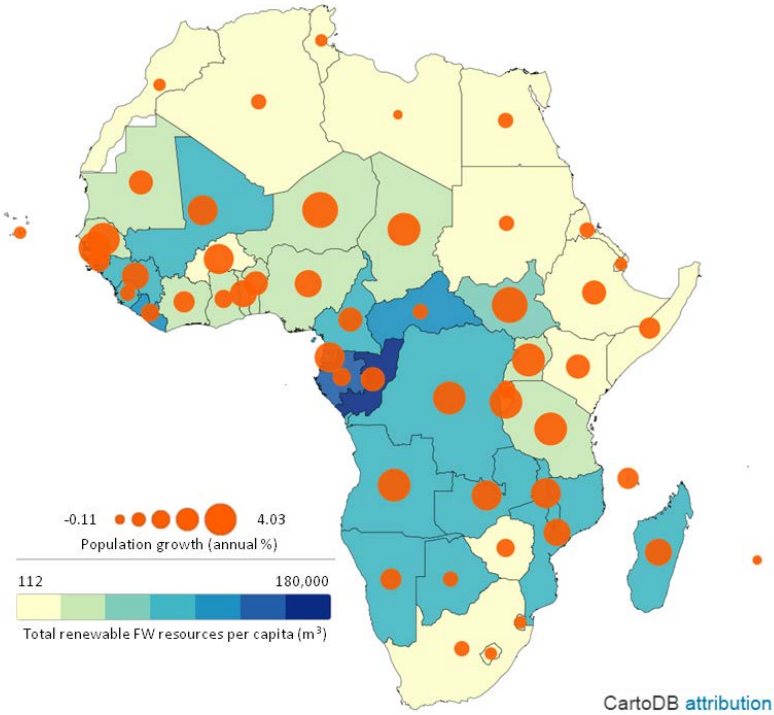

Figure 5: Total renewable freshwater resources per capita and population growth. Data: World Bank (2016)

A shortcoming of using TOTRENCAP is that this indicator does not consider the actual exploitable fraction of total renewable freshwater. Oftentimes, a large portion of renewable freshwater cannot be used, for example when groundwater aquifers are located in coastal proximity. Overexploitation would lead to salt water intrusion and sometimes freshwater cannot be accessed at all, because it exits into the ocean via subterranean channels. The exploitable fraction also excludes the minimum flow that is necessary to sustain flora and fauna in aquatic ecosystems of rivers. Further, several countries practice seawater desalination. For comparison, Annex 3 provides a table listing exploitable fractions and adjusted ratios of abstraction over available resources.

5.2.2. Relative Dependency on Surface Water and Groundwater

As previously discussed, energy intensity depends largely on the choice of water source, with a large disparity between surface and groundwater. Figure 6 shows the cumulative surface water and groundwater contributions to total renewable freshwater available in the given countries. It must be noted that a potential overlap is not reflected. Democratic Republic of Congo (DRC) and Republic of Congo (COG) are not displayed, because their size distorts the graph. The DRC counts 1,290 and 421 billion m^3 surface and groundwater, respectively, alongside 832 and 122 billion m^3 in COG. All water stressed and water scarce countries are placed among countries with low groundwater reserves in absolute terms, except for Ethiopia, Nigeria, Morocco and Uganda. Ethiopia and

Nigeria are both water stressed and are Africa's two most populated nations. This plays a role as the Falkenmark Index is based on population size. Uganda is also water stressed, while Morocco even suffers from water scarcity. They rank 9th and 10th in population size. It can be assumed that they strongly rely on groundwater pumping. Countries ranking 3rd to 8th place are all positioned to the left of these, among the groundwater-rich countries. They have significantly higher total freshwater available in absolute terms, with which to cover their demand.

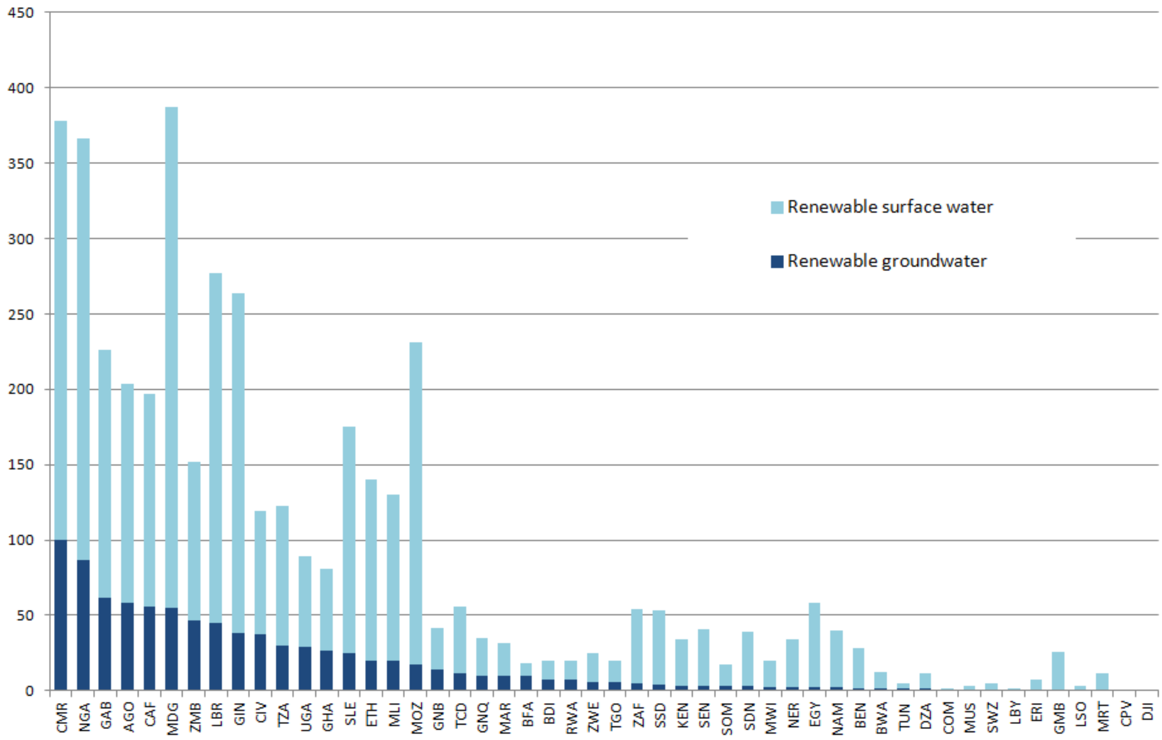

Figure 6: Cumulative renewable surface water and groundwater, ordered from largest to smallest groundwater reserves. Data: FAO (2016)

Figure 7 ranks countries by their ratio of surface over groundwater, which is an approximation to their relative source dependency. Countries towards the top have a several times larger volume of surface water than groundwater and therefore a higher relative dependency on surface water, while countries at the bottom have a high relative dependency on groundwater. Gambia ranks first with 50 times more surface water than groundwater. Burkina Faso, Libya and Comoros have a ratio smaller than 1, which means they have more groundwater than surface water.

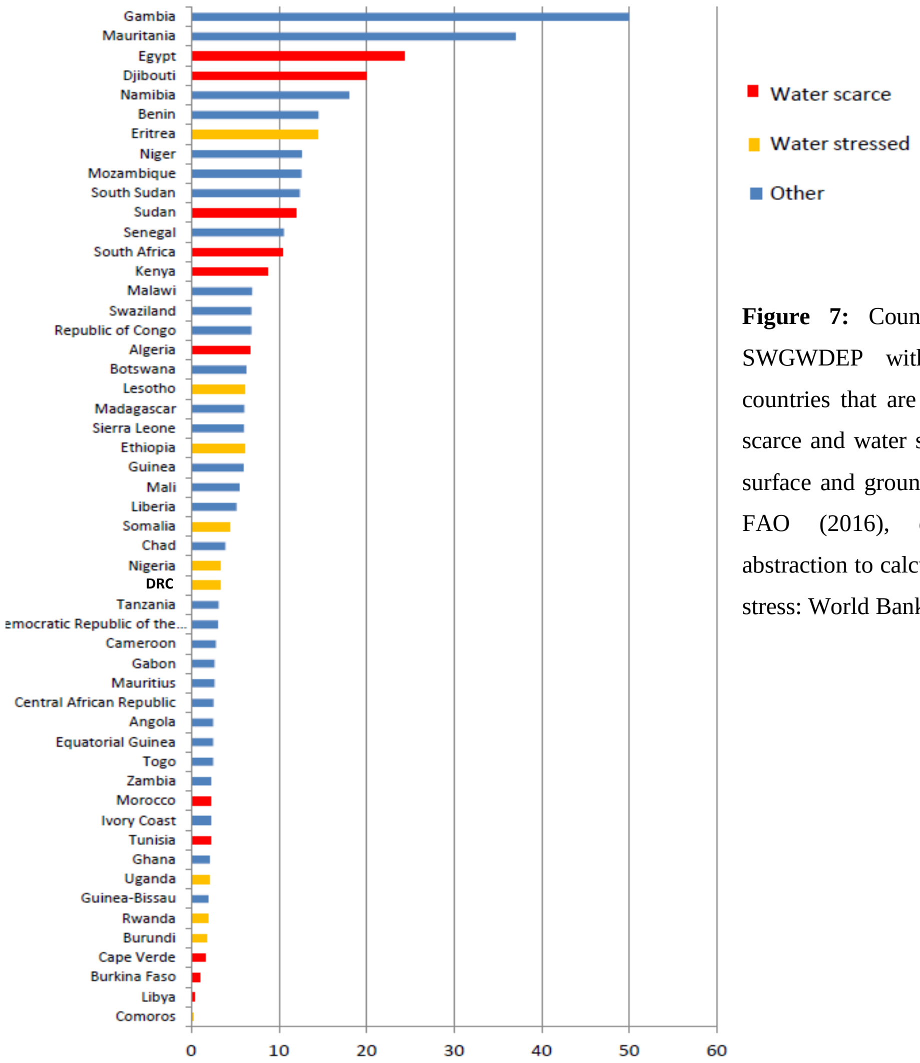

Figure 7: Countries ranked by SWGWDEP with indication of countries that are physically water scarce and water stressed. Data for surface and ground-water reserves: FAO (2016), data for total abstraction to calculate scarcity and stress: World Bank (2016)

Particularly the three countries with the lowest SWGWDEP value, but also the other water scarce and water stressed countries towards the bottom may face high costs for groundwater pumping. Countries at the top are relatively surface water dependent. The top-ranked countries can be assumed to have lower pumping costs even than water abundant countries at the bottom. The figures in Annex 4 illustrate a tendency of countries with high electricity cost splits to be located among relatively groundwater-dependent countries. This indicates that groundwater pumping is responsible for a large share of total electricity consumption by water utilities in Africa despite potential distortions due to electricity prices and pressure requirements from topography.

5.2.3. Energy Intensity of Groundwater Pumping by Depth

Figure 8 displays estimated groundwater tables across mainland Africa. Based on ranges of depth in metres below ground level (mbgl), it is possible to estimate energy needed to pump water to the surface.

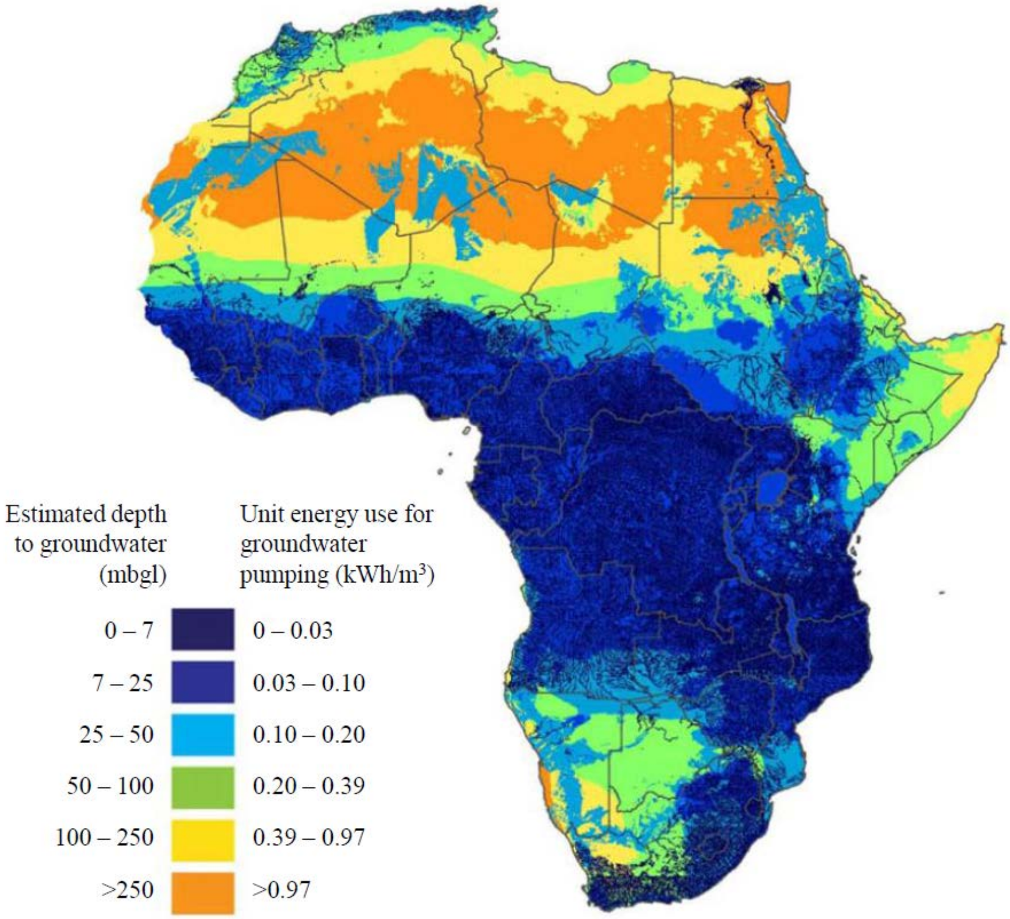

Figure 8: Estimates for groundwater depth across the African mainland with ranges of groundwater tables and corresponding kWh/m^3 needed to pump water to the surface. Contains British Geological Survey materials © NERC (2011), permission granted to modify and publish, see http://www.nationalarchives.gov.uk/doc/open-government-licence/version/3/.

Unit energy requirements (kWh/m^3) are calculated as follows (Fraenkel 1986):

$$E = \frac{\rho g H Q t}{e}$$

where P=pumping energy (Wh), ρ=density of the water (1000kg/m^3), g=gravitational acceleration constant (9.81m/s^2), H=vertical height or well depth (mbgl), Q=flow rate (m^3/sec) and t=pumping duration (h). The benchmark value used for Q is 3.785m^3/min, which is the average flow rate for a 60 hp submersible turbine pump. This is a typical model for municipal application and used for a similar cost estimation in Job (2010). The combined pump and motor efficiency of 70% was used, which is a minimum for properly operating devices (Ibid; Siddiqi and Anadon 2011). Zero pipe friction is assumed and a constant head over 12 hours a day, which is a common duration in municipalities (Job 2010). The calculation does not include the pressure requirement at the outlet, but this parameter is independent of the groundwater table.

Figure 8 helps to explain why the difference between total renewable freshwater and the exploitable amount is so large in South Africa (see Annex 3). Groundwater resources are concentrated along the coastline, where excessive withdrawal leads to salt water intrusion. Further from the coast, groundwater tables are estimated at 50–100 mbgl. Libya barely has groundwater within 50 mbgl and nearly all are located at the coast. Morocco and Algeria face similar conditions. Tunisia's northern aquifers are easily accessible, while in the south they are often brackish. Egypt benefits from a large surface water flow, contrary to Libya. In Namibia, the 25–50 and 50–100 mbgl ranges dominate average groundwater tables. This is relatively low, but Namibia ranks among the top five for its SWGWDEP value, indicating little abstraction from subterranean water bodies. Tunisia, Morocco, Chad and Somalia are countries with SWGWDEP of less than 5 and groundwater levels hovering at an average 50–100 mbgl.

5.2.4. Water Quality

Data on pollutant types and concentrations are very rare for Africa. Monitoring stations in only 14 countries report water pollution data to the Global Environment Monitoring System (GEMS) of UNEP. Latest available data is often before 2000. However, spatial water quality modelling as done by Ouedraogo et al. (2016) and Reder et al. (2014) have attempted to fill the gaps on a pan-African scale. Ouedraogo (2016) found that precisely areas with shallow groundwater experience a "very high" pollution risk, especially in densely populated areas and regions with strong primary sector production (also: Reder et al. 2014; UNEP 2010). The map in Annex 5 shows population densities on sub-national level.

Groundwater supplies 75% of Africa's drinking water, but often it is treated insufficiently. Therefore, water utilities spending only little on energy due to easily accessible groundwater may be facing a lot higher energy intensity if higher drinking water standards are enforced. Population density is a huge pressure on water quality in many African countries as access to improved sanitation and wastewater treatment is often confined to urban areas. A continental average 55% of the urban population is connected to sanitation facilities, but almost two thirds live in rural areas (PACN 2010).

5.2.5. Municipal Water Demand

Current annual municipal water withdrawal per urban inhabitant is below the OECD mean (155m^3) in every African country except Mauritius (426m^3). Volume itself cannot be seen as a pressure to energy intensity of water supply, because it is so low. However, with economic growth it will expand and water utilities may have to adapt their municipal supply grids rapidly. According to the Consumer Council for Water (2016), the average low value of household water consumption per person in a five-person household is 27m^3 per year.[2] Among the 51 countries in figure 9, 15 countries rank lower than this value. In the event of economic growth, they will face the greatest challenge to keep up with an expansion of demand and build a robust supply and wastewater infrastructure. The current mean value for African countries is at around 50% of the average in OECD countries, indicating large potential for expansion.

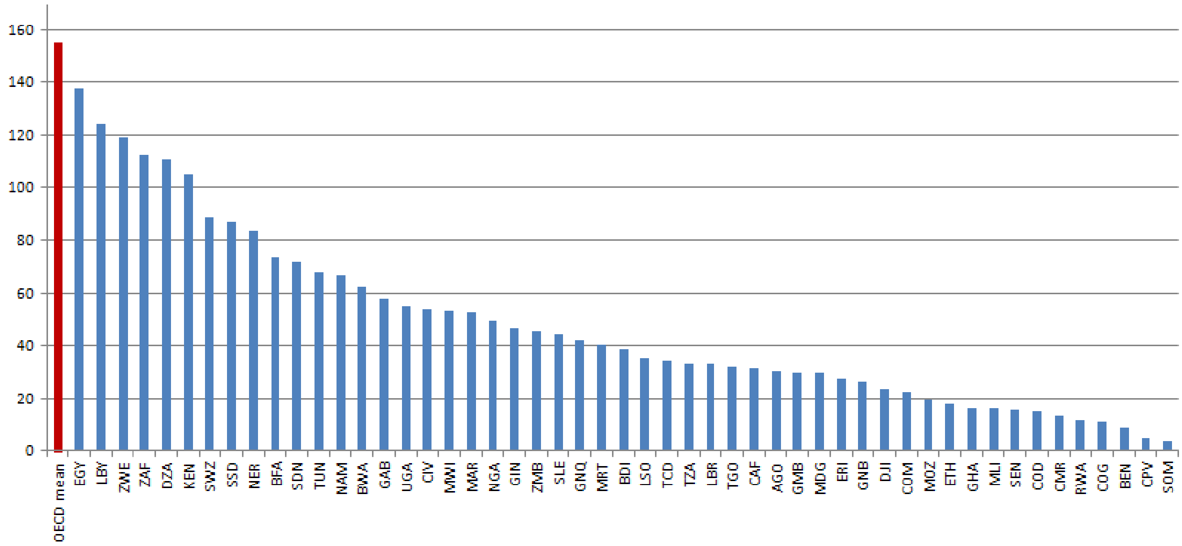

Figure 9. Average annual municipal withdrawal per urban inhabitant over the year 2014. The far left value is the OECD mean. Mauritius (426.31m^3) is excluded. Data: World Bank (2016)

Africa is the continent with the fastest growing population relative to its size and economic growth projections are favourable to a rise in living standards, albeit the imminent threat of resource scarcity and pollution. Chapter 6 presents how drivers of municipal water supply and demand are pressuring energy efficiency across countries.

[2] Note that municipal water supply covers commercial and public buildings as well.

6. Investigation of Drivers in African Countries

6.1. DRIVERS OF FRESHWATER RESERVES FOR MUNICIPAL USE

6.1.1. Competing Interests: Agriculture and Industry

Figure 10 displays the relative contributions to total water withdrawal by agriculture, industry and the municipal sector. The countries are ranked by their abstraction as a fraction of total renewable freshwater resources in ascending order. The relative apportionment indicates the relative weight by sector on water resources. A productivity increase, or a change in water intensity, will have a stronger impact in a region, where the same sector is responsible for a large portion of freshwater withdrawals.

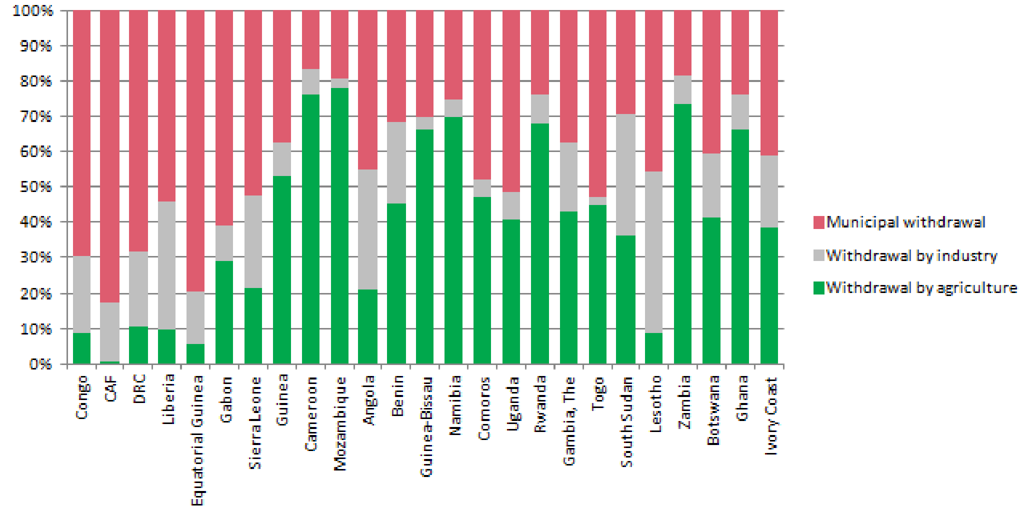

Figure 10a: Withdrawal by sectors as fraction of total withdrawal, in countries with TOTABST/TOTREN < median (water rich), ranked smallest to highest TOTABST/TOTREN. Data for 10a and 10b: World Bank (2016)

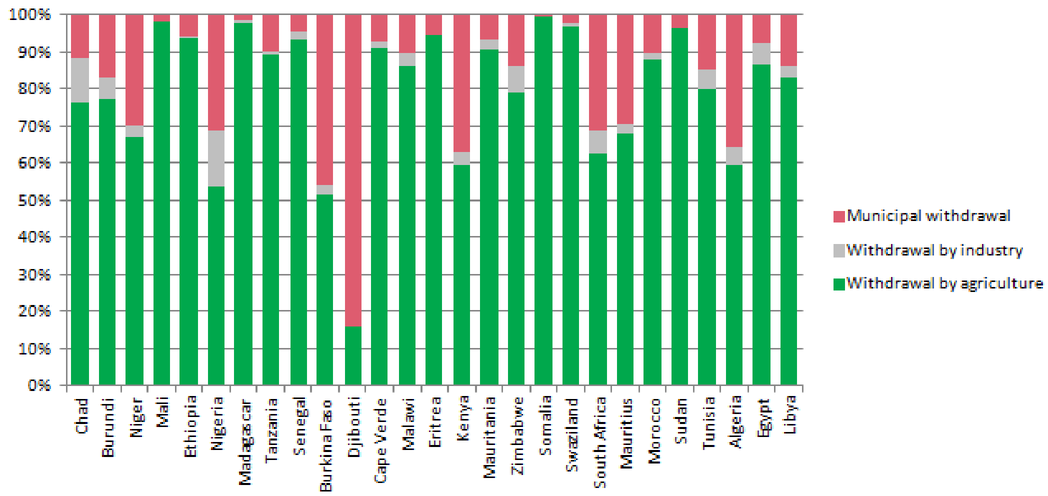

Figure 10b: Withdrawal by sectors as fraction of total withdrawal, in countries with TOTABST/TOTREN > median (water poor), ranked smallest to highest TOTABST/TOTREN.

Figures 10a and 10b illustrate that water abundant countries tend to experience a stronger relative pressure by industry and the municipal sector, irrespective of absolute numbers. This illustrates the structural difference between water rich and water poor countries. The Central African Republic has the second lowest TOTABST/TOTREN ratio (0.05%) and the lowest contribution of agriculture to total water withdrawal (0.55%). The countries placed in the second diagram have industrial shares ranging from 0% (Djibouti) to 7.09% (Zimbabwe), except for the outlier case of Nigeria, with industry responsible for 15.0% of total freshwater withdrawal. The industrial sector contributes almost a quarter (24.2%) to Nigeria's GDP, but it is not the highest fraction among African countries. The Republic of Congo ranks first globally with 69.4%. (World Bank 2016) In 17 countries, agriculture is responsible for >80% of total withdrawal, highest in Madagascar, Mali and Somalia (in ascending order). Industry accounts for >20% of total withdrawal in 9 countries, led by South Sudan, Liberia and Lesotho (in ascending order).

Beyond relative abstraction, productivity increases indicate, whether a there is a growing threat to water resources or not. Figure 11a and b illustrate the driving forces of competing interests (agriculture and industry) as a combination of contribution to total abstraction and productivity increases. The map shows that relative contributions to total withdrawal vary with climatic conditions. Where rain fed agriculture dominates over irrigation, agricultural withdrawal is smaller irrespective of productivity compared to other sectors. Along the tropical belt, share of industry in total abstraction is larger than in arid regions, where agriculture weighs more heavily on freshwater reserves. Growth of industrial VA is strong in the far eastern countries, but also Mali, Nigeria and Equatorial Guinea display rapid growth in this sector. Ethiopia, Madagascar, Mali and Mauritania have large VA growth rates for both productive sectors.

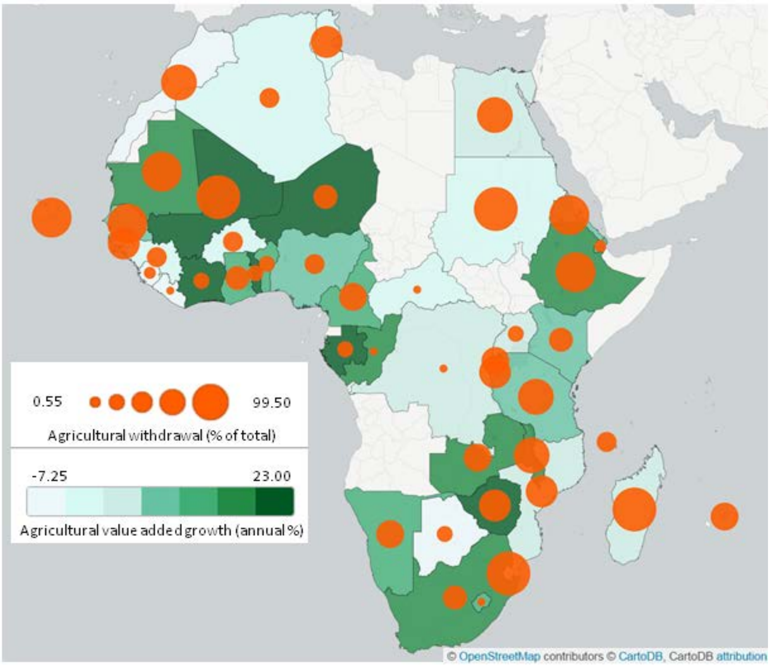

Figure 11a: Regional distribution of agricultural sector withdrawal as % of total freshwater withdrawal (shades of green) and agricultural sector value added (VA) growth in annual % (bubble area). Data for 15a and 15b: World Bank (2016).

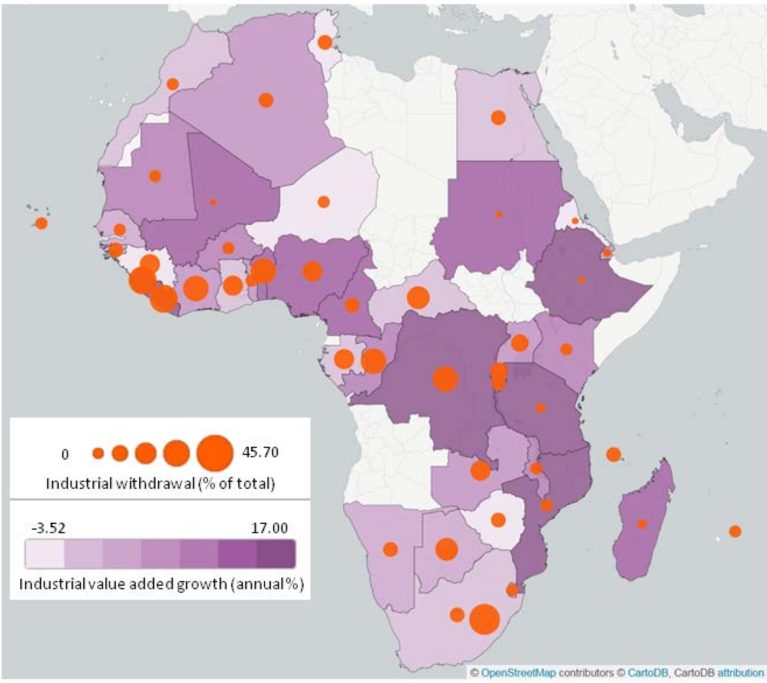

Figure 11b. Regional differences in industrial sector withdrawal as % of total freshwater withdrawal (shades of purple) as well as industrial VA growth in annual % (bubble area).

Table 8 indicates 18 countries that face the largest imminent threat in terms of sector growth and relative contribution to annual freshwater withdrawal. The countries listed have the highest share of agricultural abstraction combined with an agricultural VA growth rate of >4%. The median is given as an additional indicator, because this is not distorted by extremely large or small values, giving a more accurate image of where countries in Africa are positioned, as opposed to the mean. Tables 8, 9 and 10 are extracts of the complete data set provided in Annex 6.

Table 8: Countries with ABSTAGRI >25% and VAAGRIGROW >4%, ordered top left to bottom right by the product of the two components, and the median for all 46 countries with available values. Data: World Bank (2016)

Country	**ZWE**	**MLI**	**TGO**	**MRT**	**NER**	**MWI**	**ETH**	**ZMB**	**CIV**
ABSTAGRI	79.00	97.90	45.00	90.60	66.70	85.90	93.60	73.20	38.40
VAAGRIGROW	23.00	10.40	14.90	7.31	9.00	6.11	5.45	6.50	11.40
Country	**RWA**	**CMR**	**ZAF**	**NAM**	**GHA**	**GAB**	**BEN**	**NGA**	**median**
ABSTAGRI	68.00	76.30	62.70	69.80	66.40	29.00	45.40	53.80	67.20
VAAGRIGROW	5.26	4.66	5.57	4.63	4.65	9.69	5.12	4.27	3.50

Several countries reveal shrinking net production of the primary sector, among them are Cape Verde, Morocco and Swaziland, where agriculture extracts more than 80% of total freshwater withdrawal. This may set free freshwater resources for industrial or municipal use. But a decrease is due to drought or other causes of crop destruction, a sinking VA growth rate does not yield resources liberation for other uses.

Table 9 lists the countries with the highest pressure from industrial sector growth to available water resources. All cases below are taken from the group of countries with an annual industrial VA growth rate of >1.5% and rank highest among these by the fraction of industrial abstraction. According to the table, Liberia, Sierra Leone and DRC face the largest threat by industry. Benin, Cameroon, Rwanda and Zambia are positioned in both table 8 and table 9, therefore coping with high pressure in both sectors.

Table 9: Countries with the highest relative withdrawal by the industrial sector and industrial VA growth of >1.5%, ordered from top left to bottom right beginning with the largest product of the two components, and the median for all 46 countries with available values. Data: World Bank (2016)

Country	**LBR**	**SLE**	**DRC**	**BEN**	**COG**	**NGA**	**CIV**	**BWA**
ABSTIND	36.20	26.20	21.50	23.10	21.70	15.00	20.50	18.00
VAINDGROW	10.80	13.90	9.20	7.24	5.68	7.02	4.06	2.89
Country	**GMB**	**CMR**	**BDI**	**RWA**	**UGA**	**ZMB**	**EGY**	**median**
ABSTIND	19.2	7.07	5.90	8.00	7.85	8.27	5.86	5.43
VAINDGROW	2.66	6.80	7.95	5.78	3.94	3.50	1.52	3.59

6.1.2. Relation of Competing Interests to Total Resources and Abstraction

This section relates the impact by the productive sectors on renewable freshwater availability and total abstraction, as well as GDP per capita and GDP growth rates. Libya and Egypt are not in the graphs, because with TOTABST/TOTREN at 618% and 117%, respectively, they would distort the visualisation.

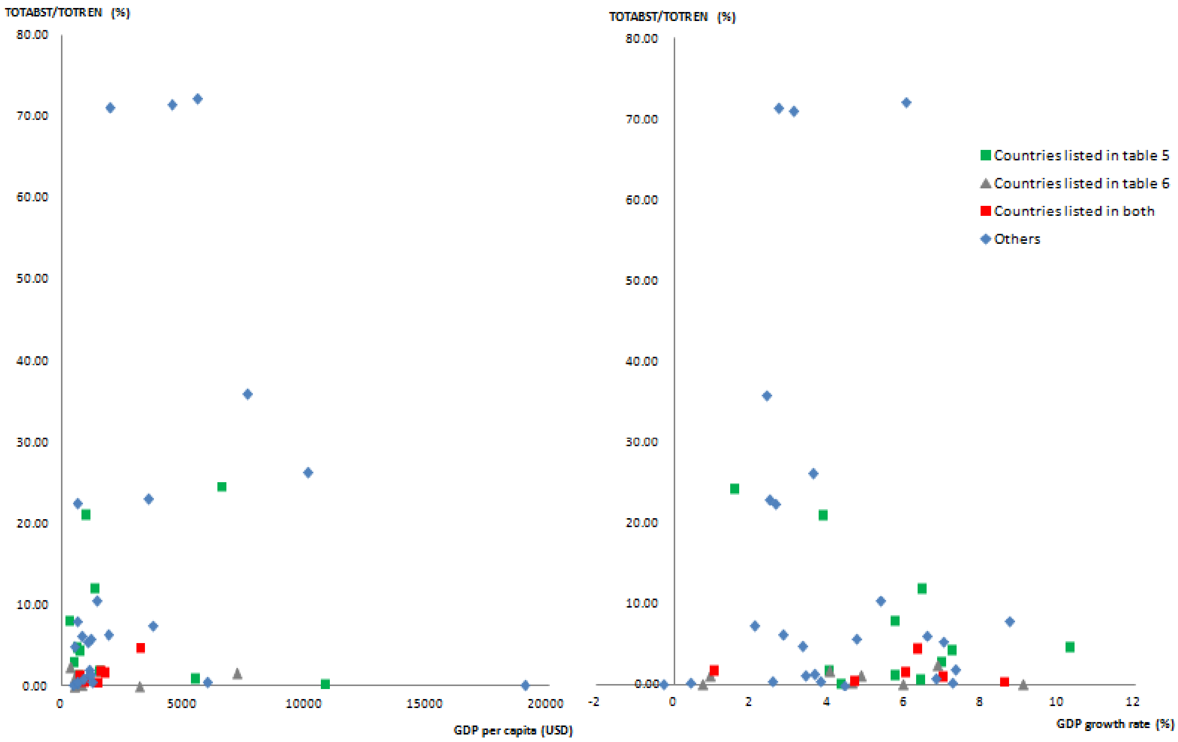

Figure 12. Scatter graph of countries by their GDP per capita and GDP growth rates (x-axis), respectively, and the ratio of annual total abstraction over total renewable water resources (y-axis). TOTREN latest available values: FAO (2016), TOTABST, GDP per capita and GDP growth rates: World Bank (2016)

The graphs show that the countries ranked as most pressured for water abstraction by both the agricultural and industrial sector are positioned at an early development stage, while their GDP growth rates are scattered across the spectrum. This is due to low fractions of municipal water use, which can be related to a number of factors such as low urbanisation, strong primary and secondary sectors in the economy, combined with high VA growth rates. The scatter among GDP growth rates indicates a significant difference to actual production increase of the competing sectors and therefore would not be suitable to explain or predict changes to water availability. The fraction of annual renewable water withdrawn is also very low. This suggests that in these cases water withdrawal by competing sectors is not a serious threat to water availability and accessible water resources for municipal use. There is room to expand total abstraction and domestic water supply does not have to move to more energy-intensive freshwater sources if withdrawal by the productive sectors increases even significantly. To capture this parameter, sector growth must be related to overall resource use and availability.

Countries ranked highest by pressure from industrial sector growth are positioned with very low GDP per capita and, again, plotted across the whole spectrum of GDP growth rates. All cases are placed with a low fraction of water withdrawn relative to total availability, except for the outlier case Egypt as a water scarce country. Although only 5.86% of total withdrawal is attributed to industry, Egypt faces high pressure by this sector relative to other African countries, which have stronger primary sectors. Countries that may expect a sharp rise in withdrawal by agriculture are predominantly positioned with a low GDP per capita, but mid-range to high GDP growth.

Land use change is an anthropogenic impact on drivers of biophysical freshwater exchange in the natural hydrological cycle. However, its complexity due to the range of parameters and close connection to climate forcing cannot be captured within the present study. Wastewater reuse is out of scope due to data limitations. However, this is a significant option only where industries do not discharge large amounts of chemically contaminated wastewater into rivers. Finally, to capture interactions by correcting drivers for the relative gravity on freshwater resources, the following compound variables are defined.

6.1.3. Compound Variables – Raw Water Extraction

This section describes all final variables reflecting the interdependencies among identified drivers. They are recalculated to normalised values (0-1).

(1) Pressure from growth in the agricultural sector weighted by its relative contribution to total FW abstraction

AGRIDRIVER expresses the pressure of an increase in net agricultural production weighted by the proportion of water abstraction relative to industry and municipal abstraction. Furthermore, concluding from figure 12, the indicator is corrected for the corresponding TOTABST/TOTREN value. ABSTAGRI, VAAGRIGROW and TOTABST/TOTREN are recalculated using z-score normalisation with:

$$z_i = \frac{x_i - \min(x)}{\max(x) - \min(x)}$$

where x_i are the country-level values of the two original vectors (x), respectively. This way the variables maintain different means and standard deviations, but ranges are the same.

The weighted indicator is the sum of the normalised sub-indicators:

$$AGRIDRIVER(V) = \sum_{i=1}^{n} z_i(v_i)$$

where $V=(v_1,v_2...v_n)$ is the vector of observed values for the previously defined variables measuring the impact of the drivers, and z_i stands for the normalised components with values $(v_1,v_2...v_n)$ for all countries. Finally, the weighted indicator is normalised for comparison with other weighted indicators, yielding a 0-1 value.

Data on VA growth is not given for all countries. For a comprehensive comparison and cluster analysis further below values for each case and all variables are necessary. For Angola, Chad, Libya and Somalia, the mean growth rates of the production of major agricultural goods in 2014 are used, with data from IndexMundi (2016). No data is available for South Sudan as it is politically contested, so the Sudanese VA growth rate is taken as a proxy. Data on Equatorial Guinea is also unavailable. Based on the size and location, similar conditions as in the two much larger neighbouring countries, Cameroon and Gabon, are assumed. Therefore, the mean value of growth rates in these two countries is used to approximate the pressure on Equatorial Guinea.

(2) Pressure from industrial sector growth

INDDRIVER expresses the pressure of an increase in industrial production as weighted by its contribution to total FW abstraction and the latest ratio of total abstraction over total renewable freshwater resources. ABSTIND, VAINDGROW and TOTABST/TOTREN are combined as in (1). The same countries are lacking data on VA growth as for the agricultural sector. Angola, Chad, Equatorial Guinea, Libya and Somalia are quantified with industrial production growth rates given by EREPORT.RU (2016). Again, no value is given for South Sudan, therefore the VA growth rate of Sudan is used for both countries.

(3) Groundwater dependency and groundwater level

GWDEPDRIVER indicates the pressure posed by high relative dependency on groundwater adjusted for varying groundwater levels. SWGWDEP is combined with the normalised values of renewable groundwater per km^2 to correct this pressure for depth of groundwater, which determines energy use for pumping. This value is useful, because there is no country-level data on average groundwater tables and the regional distribution of renewable groundwater over land area (m^3/km^2) comes quite close to the estimates modelled by NERC (2011) as displayed in Annex 7. As the annual renewable volume of groundwater per unit land area is used, fossil aquifers are excluded, therefore excluding groundwater located so deep that human pollution does not reach it. The two vectors are normalised and reversed using ($z_i' = 1 - z_i$) to correct the orientation.

The final indicators for human-made drivers of energy intensity for water abstraction are AGRIDRIVER, INDDRIVER, GWDEPDRIVER and TOTRENCAPDRIVER. For the fourth indicator TOTRENCAP is normalised and reversed. Having discussed the regional distribution of pressures to volume of water availability, the next chapter elaborates on pressures to water quality, which drive up water treatment requirements.

6.2. DRIVERS OF WATER QUALITY

6.2.1. Population Density and Population Growth

Where there is increased human activity on little space, the regenerative capacity of the environment cannot meet rising pollution. The map in figure 13 shows the different population densities across the continent and how they are met by population growth.

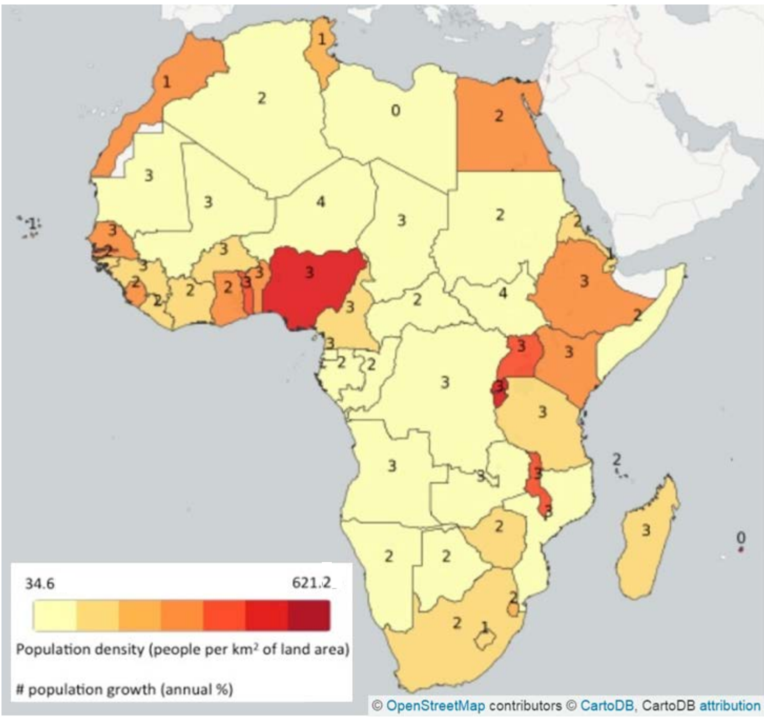

Figure 13: Population densities and population growth rates. Data: World Bank (2016)

Among countries with population densities higher than 40 per km^2, 15 countries have population growth rates exceeding 2.5%. They are listed in table 10. Guinea, Cameroon and Madagascar have lower population densities, but higher population growth rates than the median, indicating a relatively high pressure for wastewater collection and treatment to keep up with population growth as anthropogenic pollution increases in both the productive and municipal sectors, while space is constant.

Table 10: Countries with average population densities of >40/km^2 and annual population growth rates of >2.5%. Data: World Bank (2016)

Country	**BDI**	**GMB**	**UGA**	**MWI**	**NGA**	**TGO**	**BEN**	**ETH**
POPDENS	421.00	191.00	188.00	177.00	195.00	131.00	94.00	97.00
POPGROW	3.30	3.23	3.25	3.07	2.66	2.66	2.64	2.51
Country	**SEN**	**KEN**	**BFA**	**TZA**	**GIN**	**CMR**	**MDG**	**median**
POPDENS	76.20	78.80	64.30	58.50	50.00	48.20	40.50	50.30
POPGROW	3.13	2.64	2.91	3.15	2.70	2.50	2.78	2.46

6.2.2. Access to Improved Sanitation Facilities

Wastewater management practices influence water quality through coverage of wastewater collection and treatment levels. This section discusses the first driver. Rates of wastewater collection are approximated with the percentage of population with access to improved sanitation facilities, i.e. piped wastewater collection. Figure 14 displays the range of sewage system coverage across the 52 analysed countries, from 6.70% in South Sudan to 96.60% in Libya.

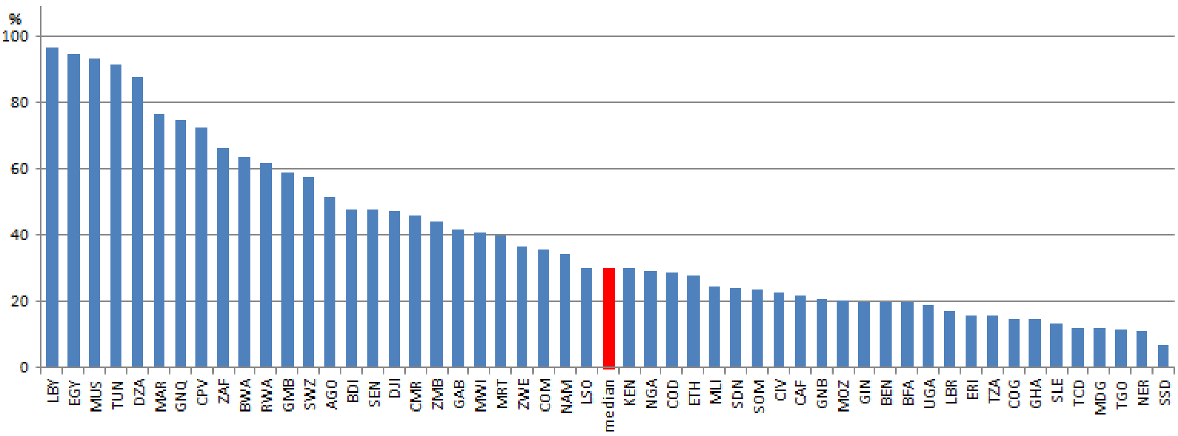

Figure 14: Fraction of population with access to improved sanitation facilities. The mean and median values are coloured red. Data: World Bank (2016)

Figure 15 shows that access is most widespread in northern Africa and to a lesser degree in the far southern countries. In the Republic of Congo, Ghana, Sierra Leone, Chad, Madagascar, Togo, Niger and South Sudan, less than 15% are connected to public wastewater collection (in descending order). As the layers in the map indicate, the countries with least access to piped wastewater collection are precisely those with the highest population growth rates. This points to a large degree of pressure on infrastructure managers to expand faster than the increase in number of inhabitants.

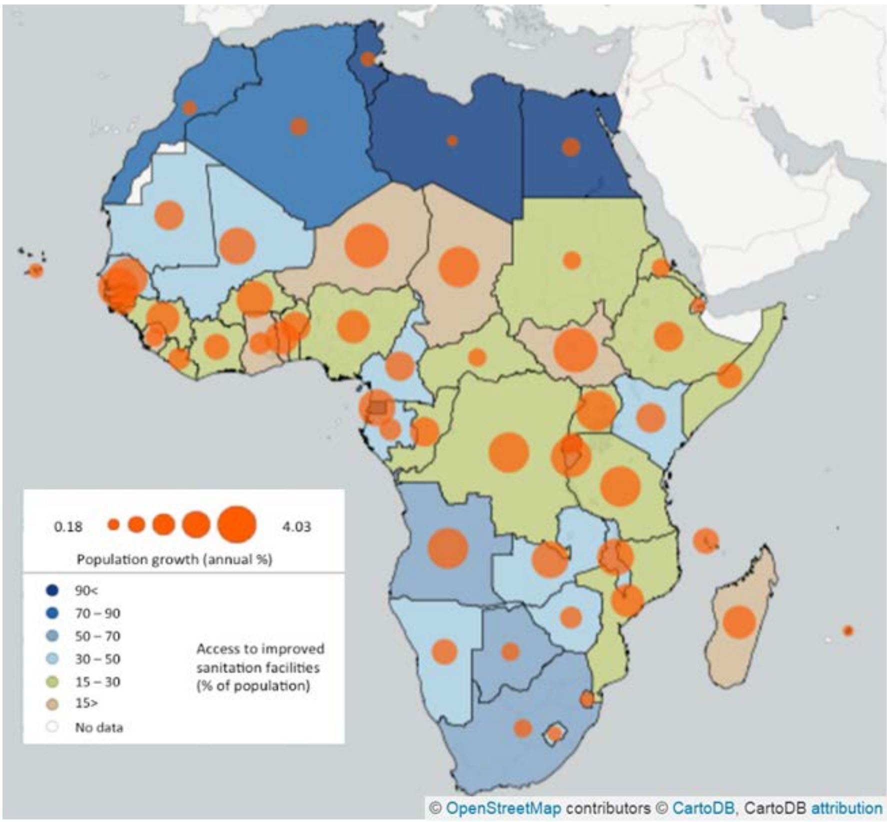

Figure 15: Percentage of population with access to improved sanitation facilities (%) layered with average annual population growth rates indicated by the bubble areas. Data: World Bank (2016)

As previously mentioned, large coverage by centralised sewage systems is not enough to estimate the systemic pressure of municipal wastewater on water quality. Treatment levels, as the degree of municipal sewage treatment, is discussed in the next section.

6.2.3. Wastewater Treatment Levels

High percentages of population with access to piped wastewater collection adversely affect water quality if treatment levels are low.

This yields the following relationship:

Table 11 illustrates the relationship between coverage of access to improved sanitation, wastewater treatment levels and water quality as found by Reder et al. (2014).

	WWTREAT low	WWTREAT high
ACCSAN low	⊖	⊕
ACCSAN high	⊖⊖	⊕⊕

Figure 16 below shows a similar picture as the range of wastewater collection in figure 15. Wastewater treatment levels are indicated by the percentage of total anthropogenic wastewater that is treated. The West African coastal countries display more advanced conditions for treatment, whereas for sewage collection there was a greater disparity between them and the far northern and southern countries. Swaziland (55.50%), Egypt (49.50%), Morocco (40.00%), Algeria (34.60%), South Africa (27.90%) and Tunisia (27.80%) treat the highest fraction of wastewater (YCELP, CIESIN and WEF 2014; Hsu et al. 2014), suggesting a low pressure on water quality in combination with high rates of access to piped sewage collection.

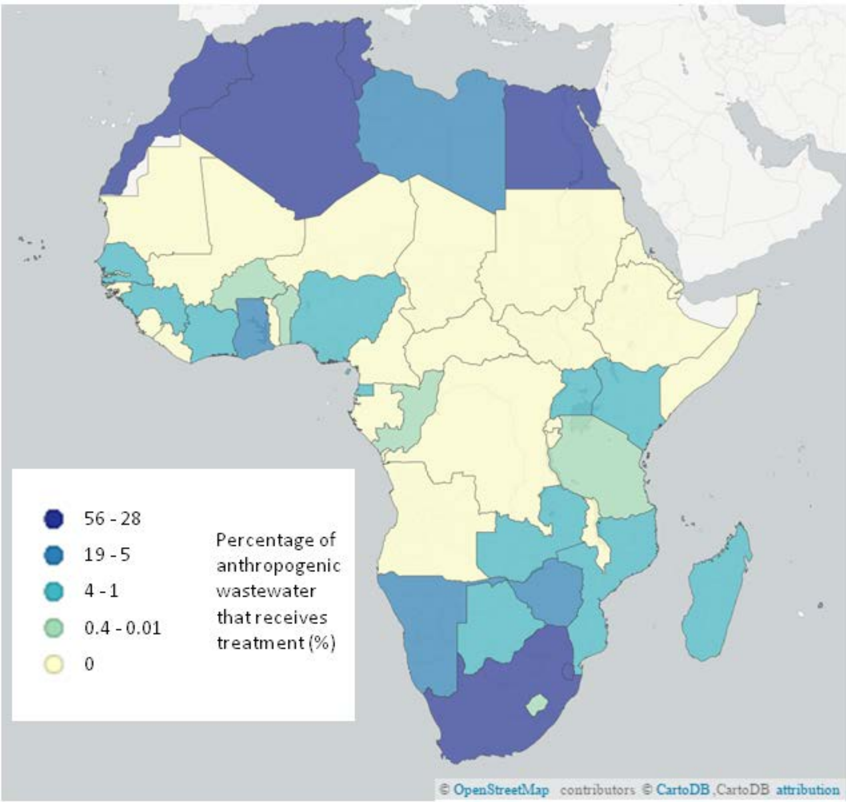

Figure 16: Levels of wastewater treatment as the fraction of anthropogenic wastewater that receives treatment (%). Data: YCELP, CIESIN and WEF (2014) and Hsu et al. (2014)

Table 12 illustrates the variation in treatment rates among countries, where more than 60% of the population is connected to centralized sewage systems. Rwanda has a comparatively high range of wastewater management, but according to available data, none of it is treated. Botswana faces similar adverse conditions. Egypt ranks highest for WWTREAT and second for WWTREAT, indicating the most preferable conditions.

Table 12: Countries with access to improved sanitation of >60% and fractions of wastewater that is treated. They are ordered from lowest to highest WWTREAT. ACCSAN data: World Bank (2016); WWTREAT data: YCELP, CIESIN and WEF (2014) and Hsu et al. (2014)

Country	**RWA**	**BWA**	**GNQ**	**MUS**	**LBY**	**CPV**
ACCSAN	61.60	63.40	74.50	93.10	96.60	72.20
WWTREAT	0	0.95	1.25	5.44	18.10	19.40
Country	**TUN**	**ZAF**	**DZA**	**MAR**	**EGY**	**median**
ACCSAN	91.60	66.40	87.60	76.70	94.70	32.40
WWTREAT	27.80	27.90	34.60	40.00	49.5	0.43

Besides municipal wastewater, the productive sectors may weigh strongly on water quality by discharging excessive nutrient loads from intensive agriculture or untreated chemical waste into aquatic ecosystems. Excess irrigation water seeps through the soil to underground aquifers, while industrial and municipal wastewater discharges are point sources and flow into surface water bodies. As previously mentioned, agricultural activity has an especially large impact on groundwater quality if groundwater tables are shallow. This relationship is discussed in section 3.2.4.

6.2.4. Pollution by the Productive Sectors in Relation to Groundwater Tables

The dilution effect can be meaningfully studied only at the local level, but a structural impact can be deduced in countries where there is a comparatively strong pressure by agricultural productivity and the groundwater table is shallow. The normalised scale of annual renewable groundwater resources per km^2 land area are chosen as a proxy to groundwater levels, as explained in section 6.1.2.

As agriculture primarily pollutes groundwater, differences in relative surface water to groundwater ratios translate to a different impact on energy needs for drinking water treatment. Assuming that a high SWGWDEP value means tendency towards surface water withdrawal for municipal water supply, the impact of nutrient loads from agriculture have less impact on energy use for purification than in countries, which withdraw a larger proportion of groundwater. Consistently, also the intensity of industrial and municipal drivers of purification requirements depends on the prevalence of surface water over groundwater use.

A shortcoming of the previous definitions of indicators is the uncertainty of actual pollution loads, i.e. fertiliser and pesticide applications as well as the shares of chemical and mining industries in these countries. Due to lack of data, their analysis is beyond the scope of this study, although it would do great lengths in giving a more accurate image of the threats to water quality and treatment requirements.

6.2.5. Compound Variables – Drinking Water Treatment

(1) Population density weighted by population growth

POPDENSDRIVER indicates the pressure of population density adjusted by population growth rates.

(2) Wastewater collection and treatment rates combined with relative source dependency

WWDRIVER represents the pressure on water quality as a combination of wastewater collection and treatment levels weighted by the relative source dependency as a high relative dependency on surface water suggests a higher pressure on treatment requirements caused by wastewater discharge. Both ACCSAN and WWTREAT are reversed using $1 - z_i(x_i)$. Further, ACCSAN and WWTREAT do not simply improve water quality by adding up. As mentioned above, if ACCSAN is very high but WWTREAT very low, the impact of municipal wastewater on receiving waters is worse than if ACCSAN is lower when WWTREAT is low. (Reder et al. 2014) This relationship is captured by the coefficient $a_{(WQ)}$, which is defined as the parabolic relationship between the difference of the normalised values of ACCSAN and WWTREAT (range 0-1).

$$f(x) = (-1)(x^2) + 1$$

$$a_{(WQ)i} = (-1)[\, z_i(ACCSAN_i) - z_i(WWTREAT_i)]^2 + 1$$

If there is a large disparity between wastewater collection and treatment rates, water quality is threatened most strongly. This is true for both high positive and negative values. High positive amplitude indicates that access to sanitation is widely in place, while treatment levels are low. A high negative difference indicates that treatment levels are high, but wastewater collection covers only a small fraction of human waste, which means that water quality is again threatened more strongly than if the difference is low. As $a_{(WQ)}$ does not reflect whether the absolute values of WWTREAT and ACCSAN are high or low, it is multiplied with the sum of the two components as follows:

$$\gamma_i = a_{(WQ)i} \sum_{i=1}^{n} z_i(WWTREAT_i), z_i(ACCSAN_i)$$

Using $a_{(WQ)}$ as a coefficient reflects the relationship better than if it is included as an addend. A comparison of both calculations is given in Annex 9. A difference in effect between positive and negative differences is irrelevant, because the following is true for all cases: ($ACCSAN_i$ – $WWTREAT_i$) > 0. In words, the fraction of population with access to sanitation is always larger than the percentage of human wastewater treated.

To summarise, if coefficient $a_{(WQ)}$, ACCSAN and WWTREAT are high, but surface water to groundwater dependency is low, this yields the least impact on water quality and is therefore represented by the lowest value of WWDRIVER. Therefore, the product γ_i is reversed to capture that low values mean high pressure. SWGWDEP plays a role as high relative dependency on surface water leads to a higher impact on treatment requirements for potable water if surface water is more severely polluted by municipal wastewater. The compound variable to indicate the pressure of municipal wastewater management on treatment requirements is defined as follows:

$$WWDRIVER(V) = \sum_{i=1}^{n} (1 - z_i(\gamma_i)), z_i(SWGWDEP_i)$$

where $z_i(v_i)$ is the normalised value of each component, respectively, and $V=(v_1,v_2\ldots v_n)$ is the vector of observed values for each of the variables.

(3) Pressure of water pollution by agricultural production

WQAGRI indicates the impact on water quality as caused by increasing agricultural productivity. The compound variable is the sum of the normalised values of the following four variables: ABSTAGRI, VAAGRIGROW, renewable groundwater per land area (m^3/km^2) and reversed SWGWDEP. If SWGWDEP is low, there is a higher relative dependency on groundwater, so agriculture will have a greater impact on raw water quality for municipal supply.

(4) Pressure of water pollution by industrial production

WQIND indicates the impact on water quality caused by an increase of industrial sector productivity. The compound variable is the sum of normalised ABSTIND, VAINDGROW and SWGWDEP. If the relative surface water dependency ratio is high, the industrial sector has a stronger influence on potable water treatment requirements.

The final key indicators for drivers of energy intensity of drinking water treatment are (1) to (4). Further, upstream pollution is an important driver of water quality in the domestic country. But a model of transnational flow is necessary to capture it, which is beyond out of scope. Finally, chapter 5.3 discusses the drivers of municipal water demand, i.e. the volume that must processed by the engineered water supply chain.

6.3. DRIVERS OF MUNICIPAL WATER DEMAND

6.3.1. Urban Population Growth

Growing urbanisation leads to more inhabitants demanding potable water. Figure 17 displays the range of urban population growth rates and the median value. The graph displays a continuous range until the drop at Libya and Mauritius.

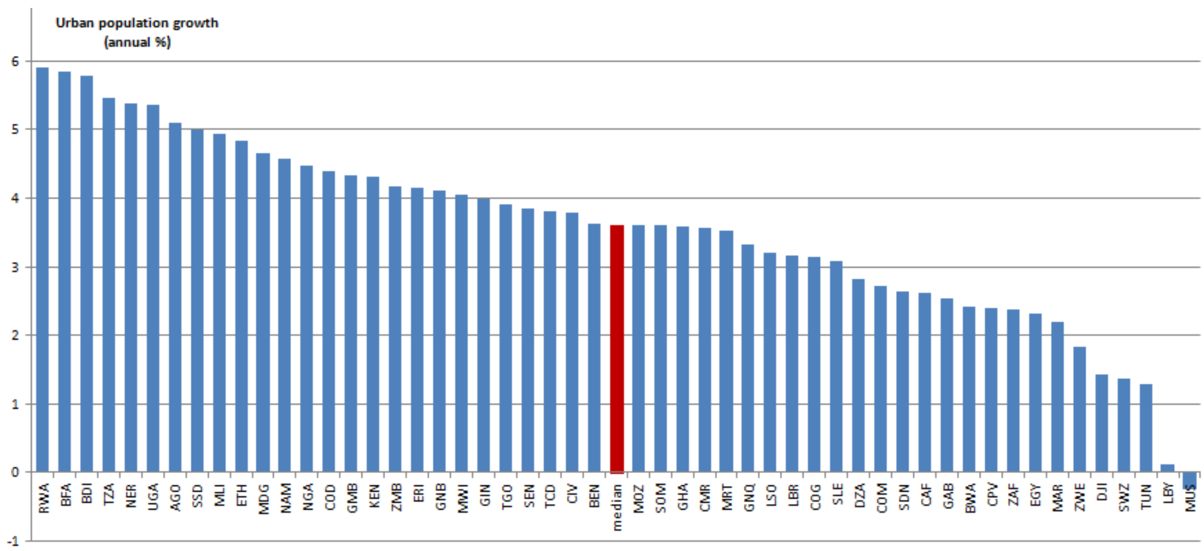

Figure 17: The range of urban population growth rates. The median value is marked in red. Data: World Bank (2016)

All but two countries with urban population growth rates >5.00% are Least Developed Countries (LDCs). In these countries, demand for municipal water can be expected to rise sharply with income growth.

6.3.2. Rising Living Standards

Rising living standards influence water demand via changes ranging from the acquisition of water-consuming household appliances to changes in habits related to personal hygiene and urban landscaping. Per capita income growth is used as a proxy. Where municipal water withdrawal per urban inhabitant is very low, a steep increase with per capita income growth may be expected until it levels out towards a saturation point. This is captured by taking the difference between the OECD mean and the country values x_i. If the difference is high, the slope of projected increase is steeper.

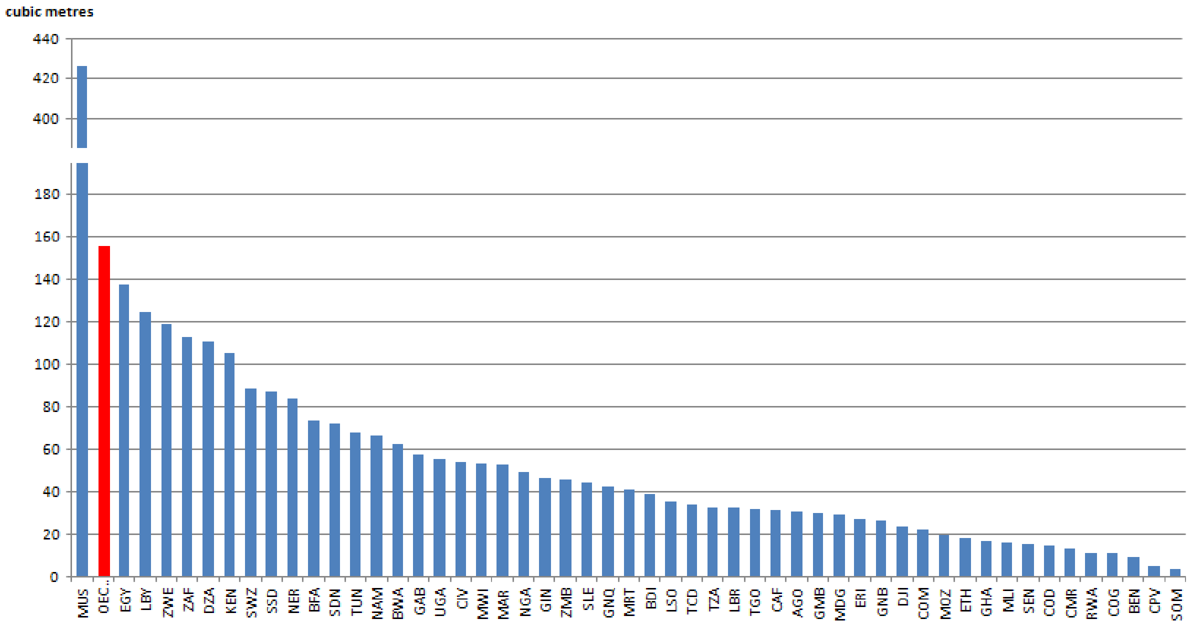

Figure 18: Average annual volumes of municipal water withdrawal divided by the number of urban inhabitants. Data: World Bank (2016)

Variance ranges from 426m^3 in Mauritius down to 3.65m^3 in Somalia. The OECD mean (155m^3) is larger than the values for all countries except Mauritius. The African median is at 39.50m^3/urban inhabitant. Per capita volume is far higher in arid regions of Africa than in more water abundant countries. Further, countries with a higher GDP appear to have higher average municipal per capita water withdrawal. The far outlier country Mauritius is a water-stressed country, yet municipal inhabitants use almost three times the amount of average inhabitants in OECD countries. According to Rai Heeroo (2013), public water utilities withdraw this magnitude, because of the volume lost to leakages, 54.40% according to IBNET data (2015). With the third highest GDP per capita among African countries, high living standards are accompanied by high water demand and as utilities must supply the double amount to compensate for losses, this amount rises even higher.

Table 13 (below) displays African countries with MUNWD per urban inhabitant of <40m^3/person (ascending order) and GDPCAPGROW >3%. Related to the OECD mean, below numbers suggest that Benin will experience the most rapid increase, with currently only 8.89m^3 per urban inhabitant municipal water withdrawn annually and a GDPCAPGROW of 3.76% in 2014. But compared to other countries in table 13, this is a relatively low growth rate. The low value indicator of withdrawal per person suggests an accelerated effect. Similarly, Angola and Eritrea, both with growth rates above 6%, can be expected to expand municipal water demand rapidly in the near future. Water utilities and public planning must be wary of the impact of these drivers in order to build resilient supply and expand the quality of water services.

Table 13: Countries with average annual municipal water withdrawal per urban inhabitant <40m^3/person and annual GDP/capita growth rates >3%. Data: World Bank (2016)

Country	**BEN**	**COG**	**RWA**	**COD**	**MLI**	**ETH**	**MOZ**
MWD/urban inh.	8.89	11.00	11.40	14.80	16.00	18.10	19.60
GDP/cap growth	3.76	4.16	4.48	4.59	4.10	7.55	4.30
Country	**DJI**	**ERI**	**AGO**	**CAF**	**TZA**	**TCD**	**median**
MWD/urban inh.	23.60	27.30	30.50	31.50	32.90	34.20	39.50
GDP/cap growth	5.66	6.41	6.66	3.31	3.65	3.82	2.18

It must be noted that in structural efficiency increases and leapfrogging are not included in the present discussion of per capita water use developments despite bearing huge potential to reduce pressure by drivers of water supply.

6.3.3. Access to Public Water Services

Figure 19 displays the relationship between municipal water demand per capita and percentages of population with access to public water and wastewater services. The plotted graph showcases a tendency of coverage with improved water services and improved sanitation facilities to be connected by a linear relationship. Further, there seems to be a generally higher rate of connection to piped water supply, while access to sewer networks is generally less expanded.

The graph also shows that there is a tendency of municipal water demand per capita to increase as access to public water services expands. But this relationship comes out only for countries with very high per capita demand, at a volume in the hundreds, i.e. closely approaching the OECD mean of 155m^3. This suggests a hyperbolic relationship, where only once coverage reaches high rates of about 90%, demand rises visibly. Further, the three groups are broadly scattered across the range of access to sanitation, while the range of connection to improved water services is far narrower within the three groups. The difference supports the finding that access to public water raises per capita demand. Outlier cases among countries marked in red are Cape Verde, Rwanda and Cameroon. All access rates and volume of per capita demand are listed in Annex 8.

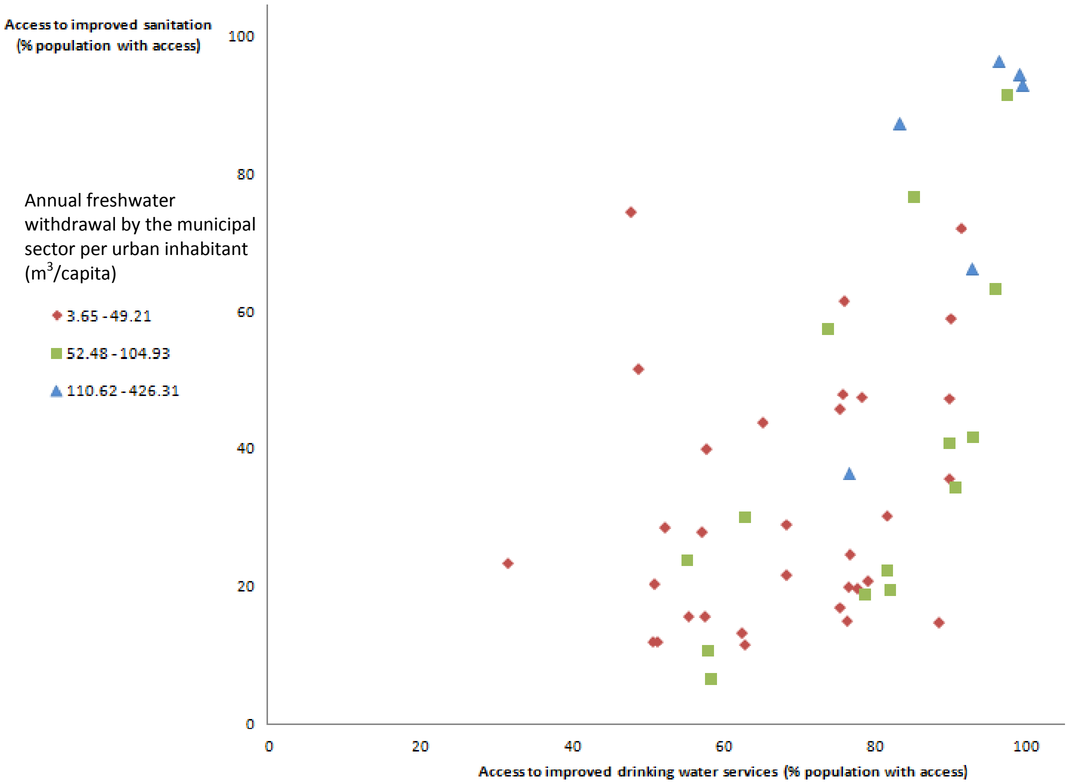

Figure 19: Countries by population with access to improved drinking water services (x-axis) and population with access to improved sanitation (y-axis). They are grouped into three ranges by annual average municipal withdrawal per urban inhabitants. Data: World Bank (2016)

6.3.4. Contribution of Non-Revenue Water to Total Municipal Water Demand

Subtracting the fraction of non-revenue water from total municipal water demand yields the residual volume that represents municipal water that is actually demanded by end-users. Figure 20 ranks countries by "pure municipal water demand", i.e. the fraction of potable water that actually reaches end-users and therefore satisfies demand. To give an impression of how water losses distort total municipal abstraction, non-revenue water is added to the bar graph in beige. For Egypt (28% water losses), South Africa (27%) and Nigeria (41%) only non-revenue water is shown in order to display the order of magnitude of water losses without distorting the dimensions of the graph as total municipal withdrawal is very large.

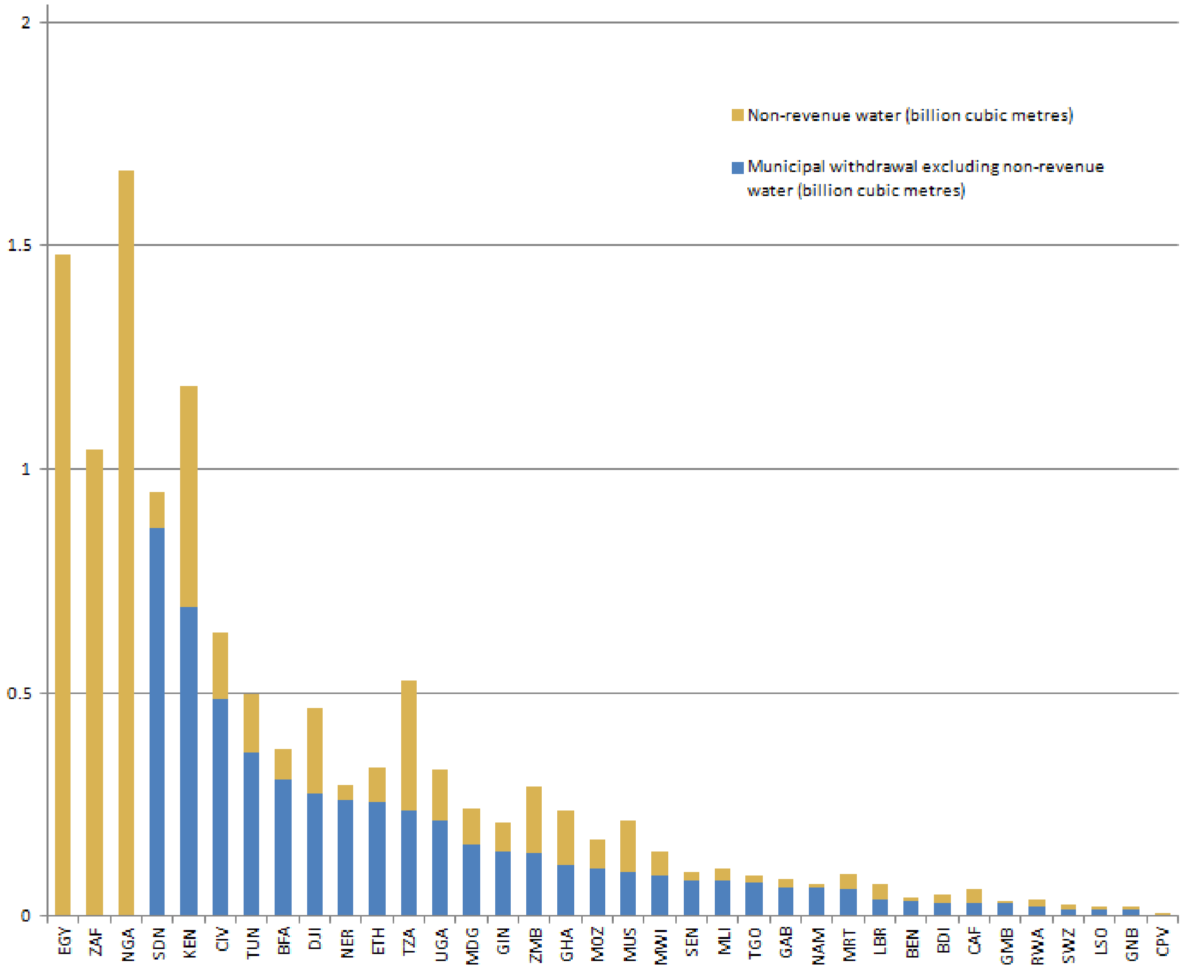

Figure 20: Countries by municipal withdrawal excluding non-revenue water ($10^9 m^3$), stacked with non-revenue water. For Egypt, South Africa and Nigeria only non-revenue water is indicated. MUNWD data: World Bank (2016); data on losses: IBNET (2015)

In Tanzania, Mauritius, Ghana, Zambia and the Central African Republic, more than half of total municipal water withdrawal is lost to the environment as non-revenue water (descending order). With infrastructure maintenance, water utilities could save 50% of operational costs. Mauritius not only looses a large fraction to leakage, but costs of electricity per 1,000m^3 water produced are among the highest in African countries with available data. Reducing water losses in this country would lead to immense cost savings and a significant reduction of energy use in an economy that is highly dependent on energy imports and carbon intensive electricity generation with around

60% by diesel engines and the remaining 40% by coal-fired plants and hydropower stations depending on the season (MBendi 2016). Tanzania and Zambia are pressured by physical water scarcity. Additionally, Tanzania experiences the highest water losses relative to total public water produced. In Zambia, the largest absolute quantity (148 million m^3) is lost to the environment. Central African Republic and Liberia both have disproportionally high costs of electricity per 1,000m^3, but in both countries about half of municipal water production is lost before reaching end-users.

Table 14: Countries with non-revenue water > 40% of total public water produced as well as Sudan (lowest fraction), the median value of all countries with available data, USD spent on electricity per 1,000m^3 of water (calculated as explained in Annex 2), E-COST% as well as maximum unit- and relative costs of electricity. Data: IBNET (2015)

Country	**TZA**	**MUS**	**GHA**	**CAF**	**ZMB**	**LBR**	**GNB**	**KEN**
NRW (%)	55.5	54.4	51.6	51.2	51.2	49.0	45.0	41.8
E-UNIT COST (USD/1,000m^3)	40.3	191.0	78.8	107.0	37.2	102.0	n.a.	16.5
E-COST (%)	17.3	31.4	25.6	17.0	13.6	35.7	n.a.	4.3
Country	**COD**	**RWA**	**NGA**	**SWZ**	**BDI**	**median**	**SDN**	**max EUC**
NRW (%)	41.3	41.0	40.7	40.0	40.0	33.3	8.7	246.0
E-UNIT COST (USD/1,000 m^3)	28.9	n.a.	21.0	89.0	107.0	42.1	42.4	**max EC%**
E-COST (%)	9.3	0.0	6.2	14.1	22.3	14.3	24.4	40.5

6.3.5. Compound variables – Volume of Municipal Water Produced

(1) Urban population growth and total population growth

URBPOPDRIVER is the sum of normalised URBPOPGROW and POPGROW. This corrects for overall population growth and the expansion of water services, which ideally connects both urban and rural inhabitants.

(2) Per capita rise in water demand

CAPDEMDRIVER is a function of rising living standards, which impute behavioural change, the expected expansion of access to improved water sources and the difference between the average municipal water withdrawal per urban inhabitant in OECD countries and the specific country value. The compound variable is calculated as:

$$CAPDEMDRIVER(V) = \sum_{i=1}^{n} z_i(GDPCAPGROW), (1 - z_i(ACCIWS_i)), z_i(\delta_i)$$

where δ_i is the difference between the OECD mean and MUNWD/urban inhabitant for each country *i*. High GDP per capita means a steep increase in living conditions with the corresponding acquisition of water using domestic appliance and behavioural change leading to higher water use. High ACCIWS rates refer to the preferable situation, where water services have limited scope to expand further due to high connection rates. This suggests a low pressure on existing public water supply and the orientation of the orientation must be reversed. Finally, a large distance between average OECD per capita municipal water consumption and the respective volume in country *i* suggests a high elasticity of demand, i.e. per capita water demand will steeply rise from initial low levels, if enabled by economic development and increased access to water services. Water losses directly quantify savings potential of electricity use and other operational costs, but due to lack of data this driver will not be included further.

The key indicators have now been translated into compound variables that quantify the level of pressure posed by a set of interacting drivers. The next section will present the regional distribution of these drivers across the countries under comparison.

7. Regional Distribution of Drivers

7.1. DRIVERS OF ENERGY INTENSITY IN RAW WATER EXTRACTION

Each of the 53 analysed countries is attributed a combination of bars indicating pressure by a set of connected drivers. Pressure is defined as the rate of increase and specific weight on water resources in the given country, based on previous literature, data on current conditions and assumptions outlined in the previous chapters.

The three diagrams in figure 21 indicate the different levels on a normalised 0-1 scale. TOTRENCAPDRIVER is above 0.8 in all cases, except for Liberia, Gabon and Republic of Congo. However, this value must be viewed with caution, because total renewable freshwater resources in Republic of Congo are 1615-times those of Libya, where the least quantity is available. The 0-1 scale does not reduce the internal disparity. Therefore, values must be taken relative to each other in this case, despite the correction by population size that is inherent to this indicator. It is positioned among the pressures not as a threat, but as a reference point.

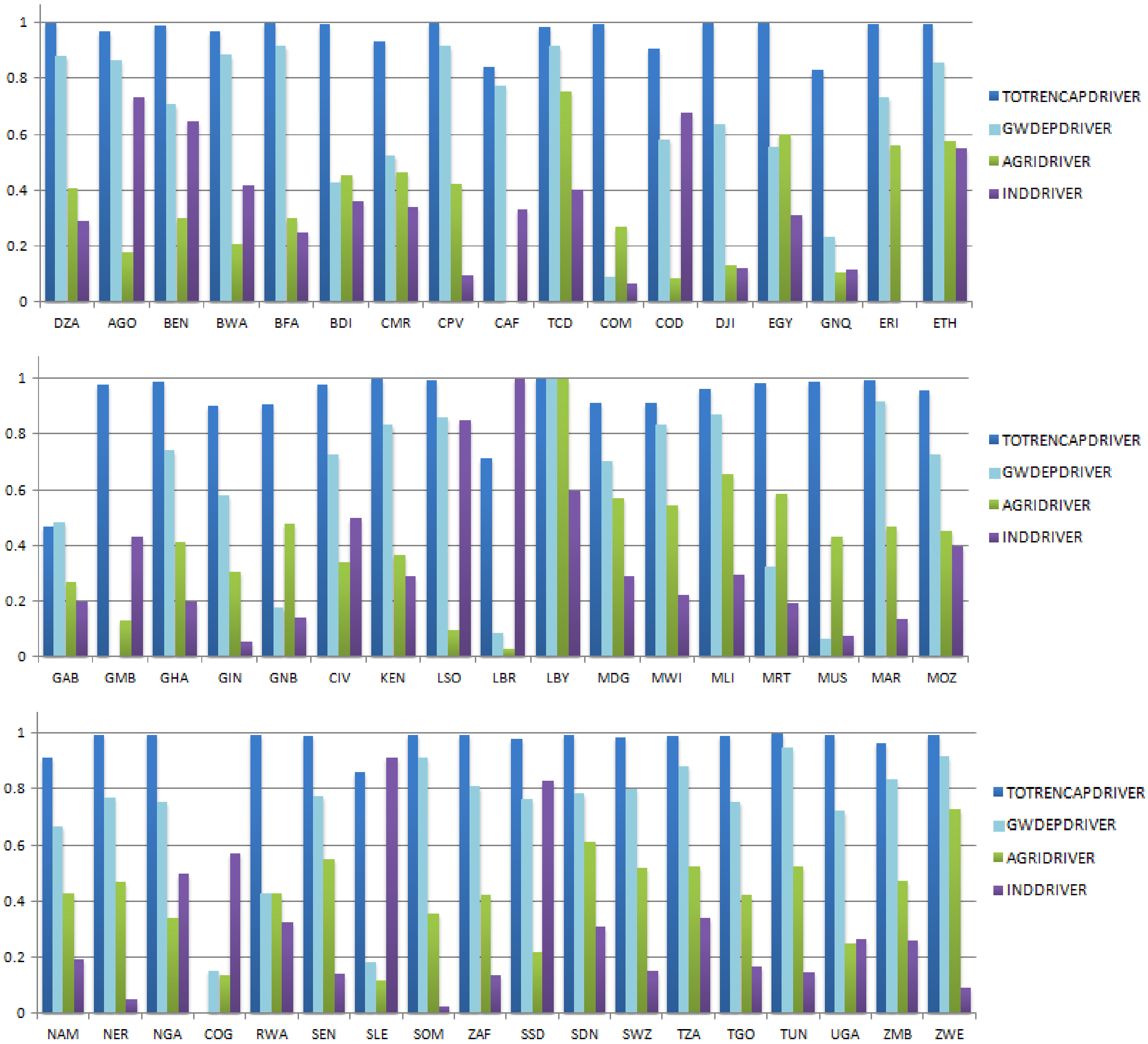

Figure 21: Levels of impact on energy intensity of raw water extraction as measured by TOTRENCAPDRIVER, GWDEPDRIVER, AGRIDRIVER and INDDRIVER.

Due to additional weighting by groundwater levels, GWDEPDRIVER displays a much higher degree of variation than TOTRENCAPDRIVER. Countries with a high relative dependency on groundwater and aquifers submerged deep underground, are marked with highest values. Cases with high relative dependency on surface water and shallow groundwater levels yield small values.

AGRIDRIVER peaks in Chad, Libya and Zimbabwe, where the agricultural sector is posing a serious threat to water availability. Several more countries are hovering around the 0.6 point mark. The pressure by industrial sector growth towers over agriculture in several cases. In Lesotho, Liberia, Sierra Leone and South Sudan, INDDRIVER transcends 0.8, while the impact by agriculture is insignificant. GWDEPDRIVER suggests that energy intensity for pumping is strongest in Libya, where recent growth rates of both agricultural and industrial production weigh heavily on freshwater resources. Top ranking countries and median values for each of the four indicators can be read from table 15.

Table 15: Countries with the highest values for each of the four indicators as well as median values. Full data is provided in Annex 8.

TOTRENCAPDRIVER		GWDEPDRIVER		AGRIDRIVER		INDDRIVER	
Libya	1.00	Libya	1.00	Libya	1.00	Liberia	1.00
Algeria	0.999	Tunisia	0.95	Chad	0.75	Sierra Leone	0.91
Djibouti	0.999	Morocco	0.92	Zimbabwe	0.73	Lesotho	0.85
median	0.99	median	0.76	median	0.42	median	0.27

The median of AGRIDRIVER values is almost twice as large as that for INDDRIVER, which indicates that a greater number of countries are facing a relatively higher pressure from agricultural sector growth than from industry.

7.2. DRIVERS OF ENERGY INTENSITY IN DRINKING WATER TREATMENT

Figure 22 illustrates the relative distribution of anthropogenic structural pressures to water quality. Burundi, Comoros and Rwanda display POPDENSDRIVER values higher than 0.8, which indicates sharp increases to population densities that are already elevated. Pressure of pollution by the three major water use sectors reveals greater consistency than among drivers to water availability. Burundi, Chad, Comoros, Guinea-Bissau, Mauritius, Rwanda and Zimbabwe are experiencing high relative pressure by agriculture, while South Sudan and most notably The Gambia see a rising pressure by industrial sector growth.

As previously mentioned, industrial effluents yield types of contaminants that order more energy intensive removal processes. This suggests that the countries with higher WQIND values will experience higher absolute energy intensities compared to countries with lower pressure by industry, even if higher values for WWDRIVER or WQAGRI are measured. However, load intensities with fertilisers, pesticides, household detergents, industrial chemicals and metals are unknown.

Figure 22 provides the levels of pressure on energy intensity of drinking water treatment faced by countries in Africa, as measured by POPDENSDRIVER, WWDRIVER, WQAGRI and WQIND.

Libya is experiencing mid-range and low-level pressure by agricultural productivity increases and municipal wastewater discharges, respectively, while POPDENSDRIVER and WQIND are zero. Therefore, water managers should focus on energy efficiency measures at the raw water extraction stage, which is where pressures are targeted in Libya. Meanwhile, countries like Burundi, Comoros, The Gambia and Rwanda show the opposite development with pressures concentrating among drivers of energy intensity in water treatment. The numbers show a strong pressure on both water availability and water quality in Chad, Liberia, Sierra Leone, South Sudan and Zimbabwe. Table 16 indicates countries, where drivers of energy intensity in water treatment are posing the greatest threat in terms of weight and potential increase in the immediate future. Here, the median values indicate more homogeneity among drivers than previously, indicating an equal level of challenge to water management across the continent.

Table 16: Countries with the highest values for each of the four indicators as well as median values. Full data is provided in Annex 8.

POPDENSEDRIVER		WWDRIVER		WQAGRI		WQIND	
Burundi	1.00	Gambia	1.00	Guinea-Bissau	1.00	Gambia	1.00
Rwanda	0.89	Mauritania	0.86	Mauritius	0.99	Liberia	0.89
Comoros	0.85	South Sudan	0.65	Comoros	0.91	South Sudan	0.85
median	0.50	median	0.46	median	0.62	median	0.41

7.3. DRIVERS OF MUNICIPAL WATER DEMAND

Figure 23 displays the level of increase that may be expected for water-demanding population growth and increase in per capita demand.

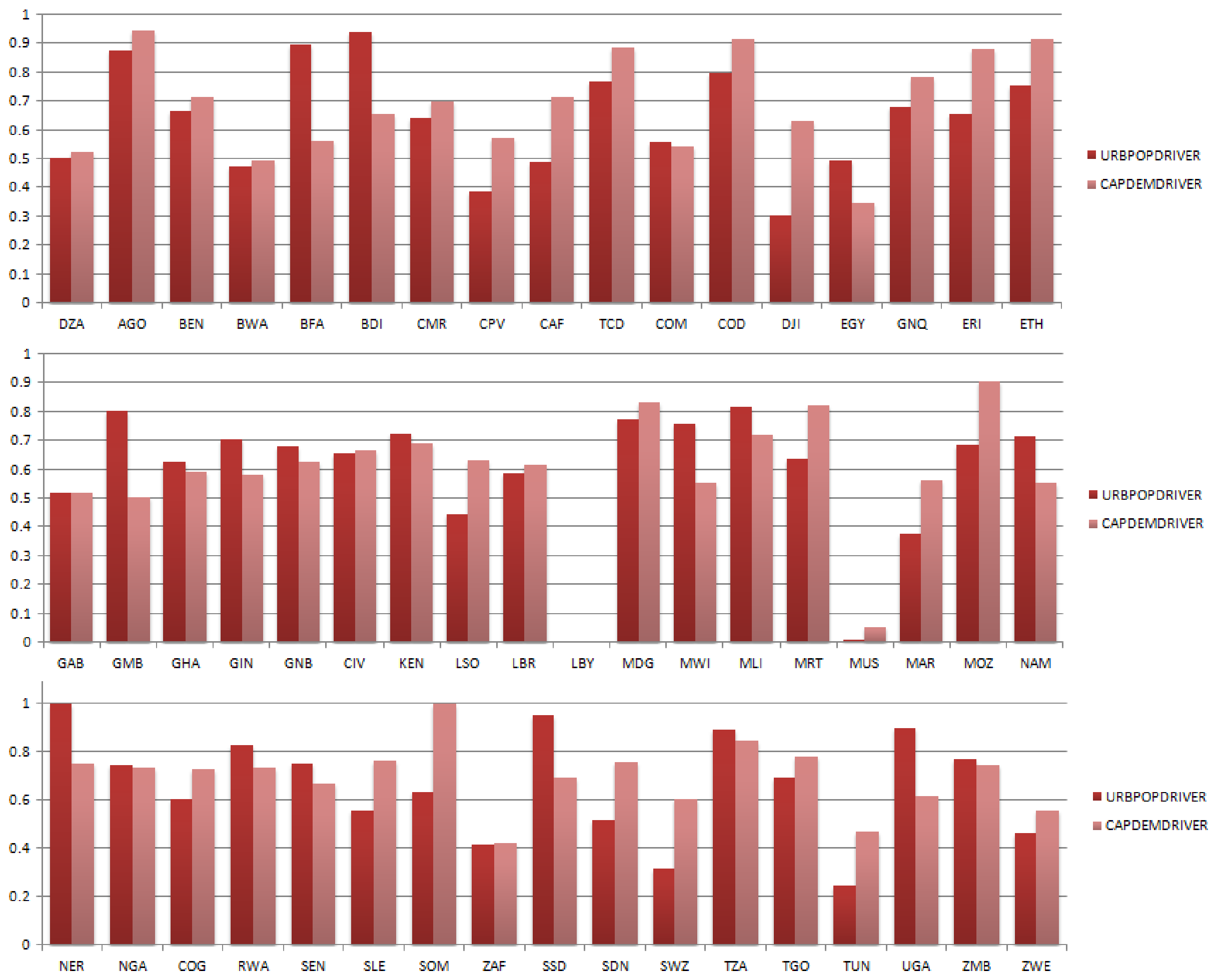

Figure 23: Indication of an increase of water-consuming urban inhabitants and potential rise of per capita demand, approximated by two sets of drivers, namely URBPOPDRIVER and CAPDEMDRIVER.

Values for URBPOPDRIVER and CAPDEMDRIVER are close together, confirmed by the similarity of median values for the two compound variables given in table 17 (below). Therefore, countries facing high population growth rates experience rising per capita demand at a similar rate. In cases with high values, this means a double-burden. Conversely, Burkina Faso, Burundi, and The Gambia rank much higher in terms of urban population growth than per capita demand. Djibouti, Somalia and Swaziland see the largest opposite disparity, where drivers of per capita demand are at play. Libya and Mauritius experience neither growth in public water demanding population, nor per capita demand growth.

Table 17: Countries with the highest values for the two indicators as well as median values. Full data is provided in Annex 8.

URBPOPDRIVER		CAPDEMDRIVER	
Niger	1.00	Somalia	1.00
South Sudan	0.95	Angola	0.95
Burundi	0.94	Ethiopia	0.94
median	0.66	median	0.67
mean	0.63	mean	0.65

7.4. DISTRIBUTION OF PRESSURES BY STAGE

The following three maps display the country-level distribution of the sum of values for each indicator by stage along the municipal water supply chain. This comparison indicates that many of the countries challenged by drivers of water pollution also experience the need to adapt to rapidly rising domestic water demand. Figure 24a displays the level of pressure caused by drivers of energy intensity at the stage of raw freshwater extraction, figure 24b illustrates pressures on energy efficiency at the stage of drinking water treatment and figure 24c provides an image of the rate at which volume of municipal water demand is expected to increase, based on the previously outlined indicators. Intuitively, countries in arid regions face greater pressure than countries in water-rich climatic zones. This is confirmed in figure 24a. Several water-rich countries are coloured dark, which is due to the combination of high production growth rates by competing sectors responsible for large portions of freshwater withdrawal with surface water over groundwater ratios suggesting the need to pump from greater depths, as indicated in the bar graph in figure 21.

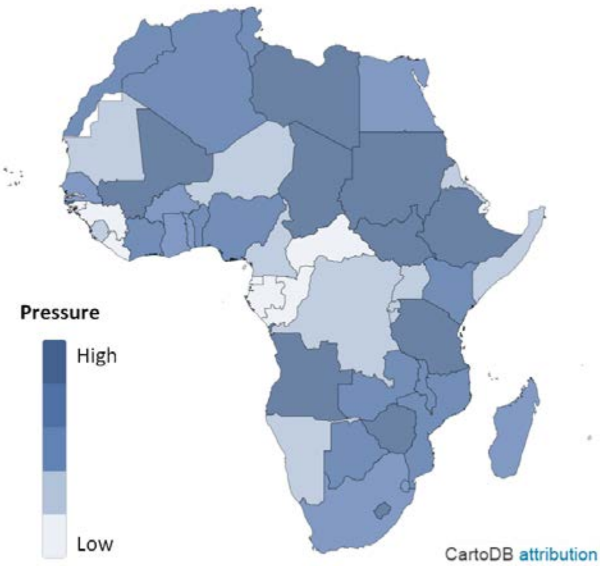

Figure 24a: Cumulative impact on energy efficiency as defined by type and size of freshwater reserves. Values are calculated as the sum of TOTRENCAPDRIVER, GWDEPDRIVER, AGRIDRIVER and INDDRIVER.

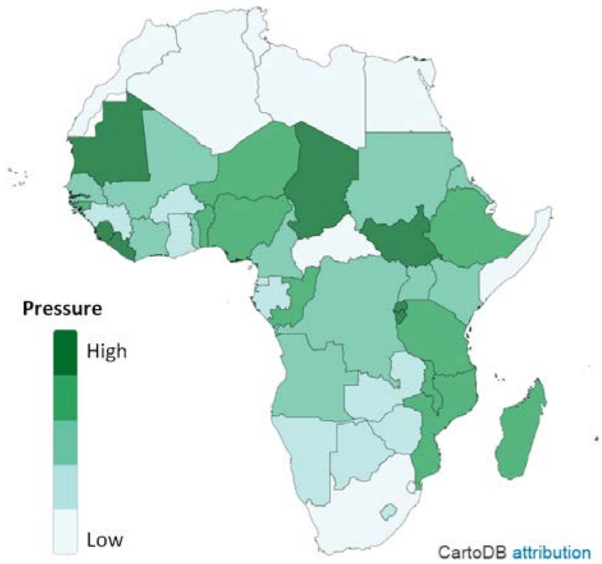

Figure 24b: Cumulative impact on water quality of available freshwater resources, taken as the sum of POPDENSDRIVER, WWDRIVER, WQAGRI and WQIND.

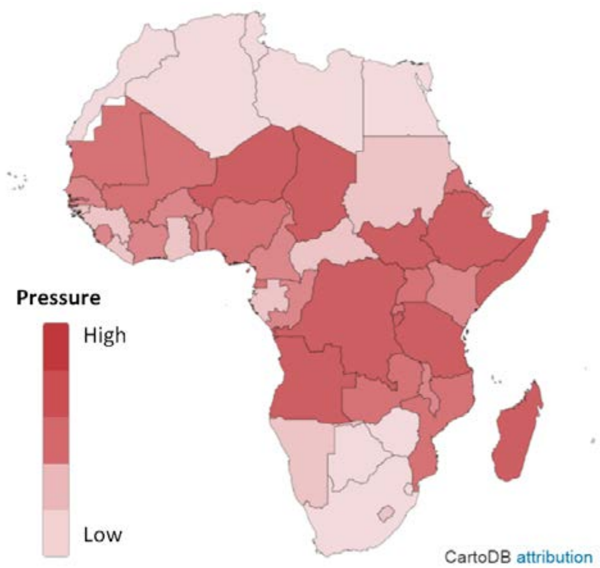

Figure 24c: Cumulative challenge on water utility managers to adapt to rising volumes of municipal water demand, as defined by the sum of URBPOPDRIVER and CAPDEMDRIVER.

In figure 24b, overall pressure to water quality appears to spare arid countries in the north and south. Municipal wastewater management in these countries functions better than countries at an earlier development stage, according to data. Further, competing sector growth is threatening water quality in fast growing economies.

Based on the quantification of drivers as pressures on freshwater resources for municipal use and water quality as well as rapid expansion of demand, chapter 7 describes a cluster analysis, which groups countries by structural similarities.

8. Cluster Analysis

The 53 countries were grouped by the ten compound variables. A hierarchical cluster analysis was performed using median linkage and Ward's method, with Squared Eucledian Distance. The common denominator of both approaches was an optimal partition at 8 clusters based on the error coefficients at the subsequent clustering stage. Supporting tables and dendrograms can be reviewed in Annex 10. A k-means cluster analysis (k=8) was performed to define narrower groups. Clusters 1, 7 and 8 contain one case, clusters 2, 3 and 4 have eight members, cluster 5 contains 4 cases, and cluster 6 is the largest with 21 countries. The outlying cases include Mauritius (cluster 1), The Gambia (cluster 7) and Libya (cluster 8). The clusters containing only one case were taken together and classified as *outliers*. Members of the five remaining clusters as well as the three singular cases are redefined as clusters 1 to 5. They are presented in figure 25. The k-means clustering produced the following final cluster centres:

Table 18: Final cluster centres as defined by the k-means cluster analysis. (OL=outlying case)

	Cluster							
	OL	1	2	3	4	5	OL	OL
AGRIDRIVER	.43	.18	.44	.51	.14	.44	.13	1.00
INDDRIVER	.08	.62	.19	.17	.67	.25	.43	.59
TOTRENCAPDRIVER	.99	.95	.98	.99	.51	.96	.98	1.00
GWDEPDRIVER	.06	.77	.71	.84	.23	.66	.00	1.00
POPDENSDRIVER	.71	.47	.42	.35	.43	.62	.74	.00
WWDRIVER	.43	.49	.60	.15	.50	.46	1.00	.24
WQAGRI	.99	.42	.48	.60	.66	.71	.00	.63
WQIND	.21	.64	.44	.31	.66	.37	1.00	.00
URBPOPDRIVER	.01	.67	.61	.40	.57	.77	.80	.00
CAPDEMDRIVER	.05	.72	.78	.50	.66	.71	.50	.00

Mauritius varies from the cluster centres of multi-case groups with a significantly lower pressure by industry, very high pressure by population density and even greater by agriculture to water quality. Low pressure on infrastructure management is derived from very low values of change in municipal water demand. The Gambia bears significantly lower pressure by agriculture and groundwater pumping requirements on energy intensity of water withdrawal, much lower agricultural pressure on groundwater quality than elsewhere, while experiencing much higher potential increases in surface water pollution by urban wastewater and industrial effluents. The Gambia also sees a very high relative pressure by growing numbers of end-users of municipal water and lower per capita demand increase than the averages among clusters 1 to 5. Libya presents an extreme case with maximum ranking among three indicators expressing impact on energy intensity in raw water extraction, which results in increased pumping from deep fossil aquifers in this case. On the other hand, volume of municipal water demand and water quality may not be expected to challenge existing water supply.

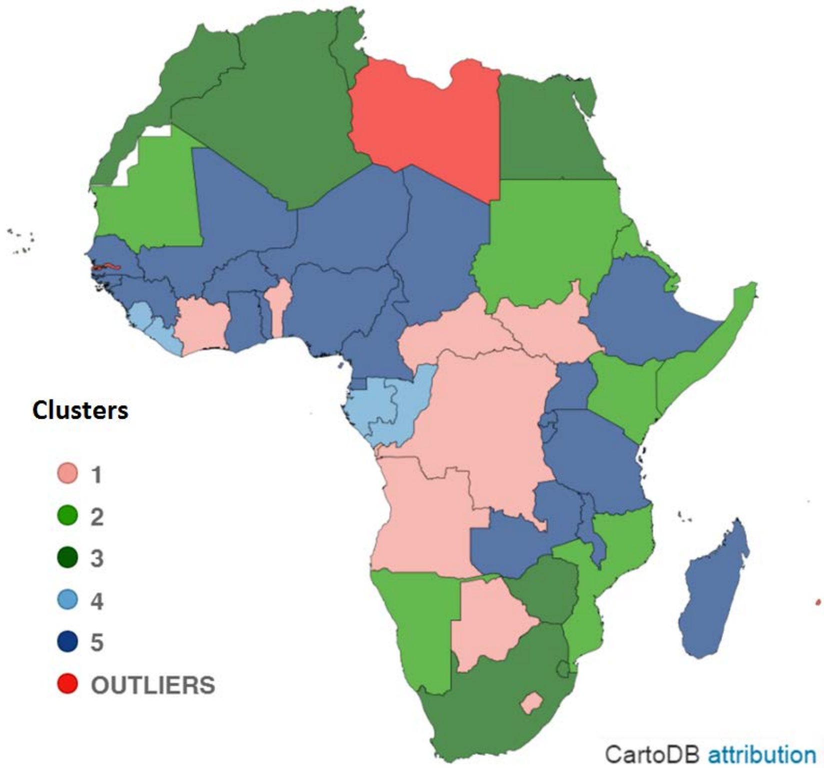

Figure 25: The five clusters of countries grouped by similar combinations of impacts as well as the three outlying cases Mauritius, The Gambia and Libya.

Countries of cluster 1, as defined in above map, set themselves apart with a relatively higher pressure by industry on availability and quality of water resources, while agriculture plays a secondary role. Apart from Ivory Coast, Benin and Lesotho, all cluster 1 countries border each other, but cover both water-rich and water-stressed zones. Interestingly, South Sudan and Sudan are not in the same cluster despite VA growth rates of Sudan used for both countries. Structural differences are enough to separate them, which suggests that analysing the two countries as a homogeneous entity, as is done in a wide range of research, may significantly distort results.

What defines cluster 2 countries, is a high impact by municipal wastewater management compared to other drivers of water quality and values of WWDRIVER in other clusters. Additionally, among all clusters, members of this group experience the highest expected increase in per capita demand for municipal water following a combination of low current demand and limited water services combined with high per capita income rise.

Countries in cluster 3, located in the far northern and southern arid zones, experience the highest pressure from freshwater withdrawal by agriculture, the lowest by industry, besides Mauritius, and the highest groundwater pumping costs besides Libya. They mark the least pressure by population density and population growth, albeit populations are concentrated in coastal areas in the North African countries, and the lowest pressure from sewage resulting from the most advanced wastewater management practices.

The four countries comprising cluster 4 are characterised by their water abundance accompanied by low pressure by primary sector withdrawal and favourable conditions for municipal water extraction. Compared to other groups, cluster 4 experiences a combination of considerable impact of both productive sectors on water quality, however much less so than in The Gambia.

In cluster 5 countries, the pressure by agricultural water consumption dominates the current pressure by industry with a significant impact on water quality in particular. These countries are located in areas with shallow groundwater levels. Here, seepage of excess irrigation water with high nutrient content reaches underground reservoirs more easily than in countries with deeper groundwater levels, where natural filtration media provide barriers to pollutants. Further, the combination of high pressure by urban population growth and increasing per capita demand indicate that municipal water supply consumes a growing portion of energy in these economies.

9. Conclusion

A comprehensive analysis of anthropogenic drivers of municipal water supply and demand was undertaken, linking drivers to requirements of energy-using processes and cumulative energy demand of public drinking water supply. The host of drivers was found to interact in a way that enabled the formation of ten key indicators that measure impact as a compound of interdependent drivers exerting pressure on resources and demand.

The analytical framework was applied to assess the variation of impacts across Africa. The results indicate how current developments are influencing energy requirements for municipal water supply and how the intensity varies among countries. Some are experiencing a rapid increase of energy intensity in either raw water extraction or at the water purification stage, others must adapt to rapidly growing drinking water demand, which drives up cumulative energy use. Several countries experience high pressure in two or three categories. Often, diverging combinations of drivers at varying intensities yield similar outcomes. This information is useful for a close examination of the components that determine such conditions and emphasises the need to consider activity in other sectors and their impact on drinking water supply.

A large crosscutting impact by growth in agricultural productivity on energy intensity in both the municipal water extraction and at the purification stage was measured. In water abundant and surface water dependent countries, industry plays a larger role. At continental scale, a larger number of countries are facing a surge of energy intensity in raw water abstraction and treatment caused by competing water use in primary sector production. Economic development and freshwater recharge are two drivers among many that determine the impact by agriculture. Therefore, the affected countries are scattered across several climatic zones and GDP per capita growth rates. By incorporating interdependencies among all identified drivers, the actual degree of impact on municipal water supply was captured more accurately than if sectors and drivers were examined individually.

Many countries identified with high impact on energy intensity in raw water extraction were found to experience low impact by drivers of water quality and energy intensity at the purification stage of the supply chain. Consistently, the opposite was found for countries with low stress on raw water extraction. But due to the strong influence of shallow groundwater, high relative groundwater dependency, economic structure and wastewater management practices, the divide between water abundant and arid countries does not always hold.

Further, a large scope for expansion of water infrastructure was observed, while municipal water abstraction per capita is very low in the vast majority of countries. This suggests that an increase of municipal water demand and supply will drastically accelerate across the entire continent as economic development, population growth and urbanization advance. Many countries have high economic growth rates that suggest available financial capacity to expand public services.

The present study also gives a detailed account of which drivers are causing rapid demand growth. This is something that water managers can prepare for. In addition to drivers of actual demand by municipal populations, much of the growing volume of public water production can be balanced by infrastructure maintenance to reduce losses from non-revenue water, especially through leakage from distribution lines.

Interestingly, demand increases appear to coincide strongly with growing water pollution. The geographic distribution is found to be very similar. Countries could improve wastewater management practices as they increase municipal water supply to curb pollution of water sources. The combination of these drivers could significantly increase energy intensity of the municipal water sector in these countries and therefore calls for immediate attention in order not to face shortages or drastic deterioration of water quality. As water utilities in these countries struggle to meet rising demand, wastewater management cannot lag behind.

Finally, the characterisation of clusters provides a base for transnational knowledge and technology sharing among countries facing similar conditions far beyond resource availability or geographical proximity and complexity. Instead, collective action can specifically target the set of drivers that are specific to this group of countries in terms of the energy-for-water connection. Outlying countries can examine the details of the conditions separating them from other cases. By understanding how driving forces set up diverging conditions compared to neighbouring countries, outliers can draw useful conclusions for nexus-consistent planning on their own ground and in other countries.

A significant limitation to this study is that some of the identified drivers must be quantified on sub-national level in order to derive site-specific impacts on energy intensity of drinking water supply. Unfortunately, this was beyond the scope of the present study. Furthermore, lack of data prevented the deserved consideration of exploitable renewable freshwater and non-revenue water. Continuing research could develop a simulation model that connects existing hydrologic, water use and water quality models, as well as topography to energy intensity of water supply. Such a simulation could use the key indicators derived from the interdependencies among drivers as outlined in the present study and convert the relative distribution of challenges into absolute values.

Nevertheless, the new analytical framework developed by the current study connects resource availability to competition with the productive sectors, characteristics of water and wastewater management, as well as economic and demographic developments. All of these feed into efficient resource allocation of water and energy. Infrastructure managers and utility operators can apply these findings to their planning considerations to identify country-specific impacts on scarce resources and build resilient infrastructure. Data supporting nexus studies deserves increased attention because in a world of growing scarcities, only crosscutting perspectives can ensure optimal resource allocation to sustain current living standards and preserve the environment.

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List of Tables and Figures

Annexes

Annex 1

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<tr><td rowspan="5">E-COST%; total unit operational costs; operational cost split, water only</td><td rowspan="5">2014: NER, RWA, ZAF, KEN, NGA, MOZ, MWI, COD, LSO, CIV, ZMB, BFA, TZA, MLI
2013: TGO, BEN, UGA, SEN
2012: ETH, BDI, CPV
2011: GIN
2010: TUN, EGY
2009: NAM, SWZ, CAF, CMR, GAB, SDN, GHA
2008: MRT
2006: MUS, LBR
2005: GMB</td><td>VAINDGROW</td><td>2014: all, except AGO, TCD, LBY, SOM and SSD (supplementary sources and corresponding years for these countries, see chapter 6.1.3, p.49)</td></tr>
<tr><td>POPGROW</td><td>2014: all</td></tr>
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<tr><td>ACCSAN</td><td>2014: all</td></tr>
<tr><td rowspan="2">WWTREAT</td><td rowspan="2">2012: all, except COM, SOM and SSD (supplementary sources and corresponding years for these countries, see chapter 4.4.3, p.33)</td></tr>
<tr><td>TOTRENCAP</td><td>2014: all</td></tr>
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2012: CPV, ETH
2011: GIN
2010: TUN, EGY
2009: SWZ, BDI, NAM, GAB, GHA, SDN
2008: CAF, MRT
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2005: GMB, MDG</td></tr>
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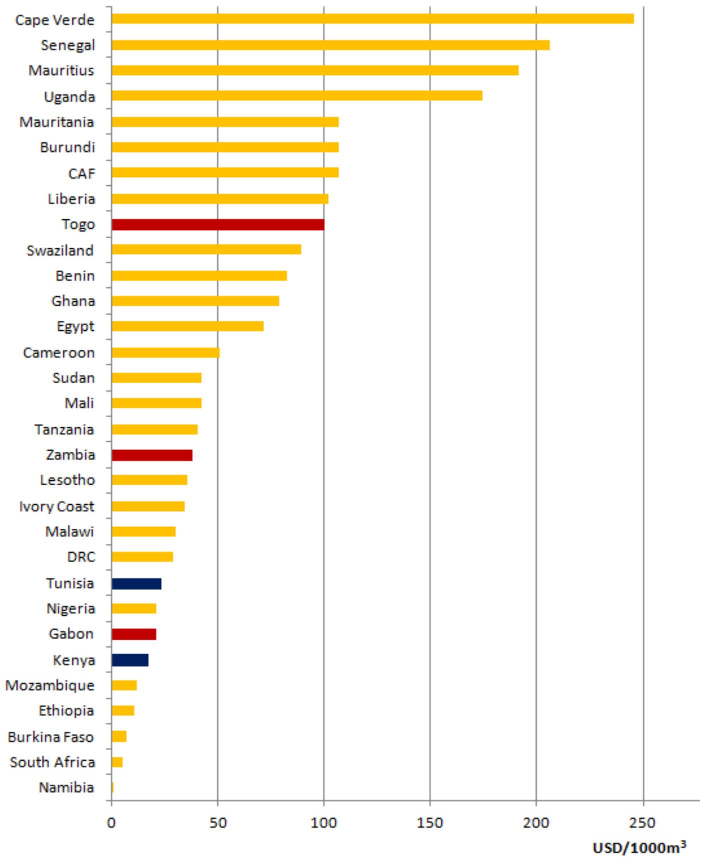
<tr><td>Total renewable surface water</td><td>2014: all</td></tr>
<tr><td>Total renewable groundwater</td><td>2014: all</td></tr>
<tr><td>ABSTAGRI</td><td>2014: all</td></tr>
<tr><td>VAAGRIGROW</td><td>2014: all, except AGO, TCD, LBY, SOM and SSD (supplementary sources and corresponding years for these countries, see chapter 6.1.3, p.49)</td></tr>
<tr><td>ABSTIND</td><td>2014: all</td><td>GDPCAPGROW</td><td>2014: all</td></tr>
</table>

Annex 2

UNITE-COST (in USD/1000m^3) = per unit expenditure on electricity, calculated as [*E-COST%*] * [*average unit operational costs*] * [*operational cost split excluding wastewater management*] * 1000. The calculation excludes countries, where E-COST% is zero. Data: IBNET (2015)

This value by itself is not suitable for comparison between countries as currency exchange rates may distort the result. However, absolute per unit costs combined with E-COST% reveal the cases that could significantly reduce their operational costs with energy-efficiency measures.

Country	E-COST%	UNITE-COST
Benin	21.33	82.44
Burkina Faso	13.72	6.86
Burundi	22.26	106.85
CAF	16.94	106.72
Cameroon	23.06	50.73
Cape Verde	36.11	245.66
DRC	9.27	28.9
Egypt	18.20	71.54
Ethiopia	15.94	10.67
Gabon	23.35	20.64
Ghana	25.60	78.82
Guinea	0.00	
Ivory Coast	11.19	34.7
Kenya	4.27	16.51
Lesotho	9.40	35.72
Liberia	35.68	101.82
Malawi	8.87	30.31
Mali	17.47	42.1
Mauritania	22.47	106.89
Mauritius	31.35	191.37
Mozambique	7.56	11.74
Namibia	1.40	0.83
Niger	0.00	
Nigeria	6.23	21.03
Rwanda	0.00	
Senegal	39.52	206.21
South Africa	2.82	4.93
Sudan	24.43	42.38
Swaziland	14.08	89.02
Tanzania	17.27	40.34
The Gambia	2.49	188.59
Togo	14.26	99.6
Tunisia	12.03	22.93
Uganda	22.32	174.64
Zambia	13.61	37.24



Annex 3

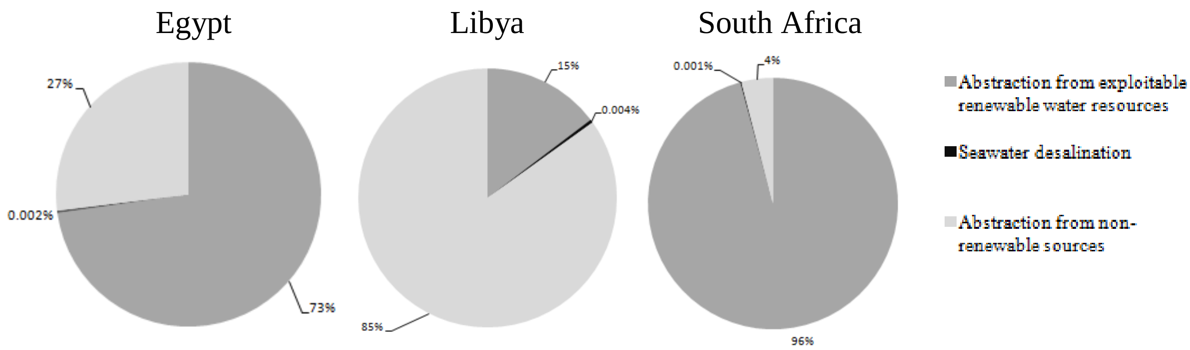
This table displays exploitable fractions and adjusted ratios of abstraction over available resources.

Country	DZA	BFA	COM	EGY	ETH	GIN
Exploitable ($10^9 m^3$/yr)	7.90	4.75	1.02	49.70	53.00	204.00
Desalination ($10^9 m^3$/yr)	0.62	0	0	0.20	0	0
TOTABST/ TOTREN (%)	72	6	1	117	5	0.24
TOTABST/ (Expl+Des) (%)	99	17	1	137	11	0.27

Country	LBY	MUS	MAR	NAM	ZAF	TUN
Exploitable ($10^9 m^3$/yr)	0.64	1.08	20.00	0.65	11.97	3.63
Desalination ($10^9 m^3$/yr)	0.02	0	0.01	0.0003	0.02	0.02
TOTABST/ TOTREN (%)	618	26	36	0.72	24	72
TOTABST/ (Expl+Des) (%)	663	67	52	44	104	91

This table presents exploitable freshwater, desalinated freshwater, the ratio of total abstraction over total renewable resources (TOTABST/TOTREN) and the ratio of TOTABST over the sum of exploitable and desalinated water. Data for total abstraction: World Bank (2016) for 2014. Data for total renewable FW, desalination and exploit. water: FAO (2016) with latest av. values (since 2005).

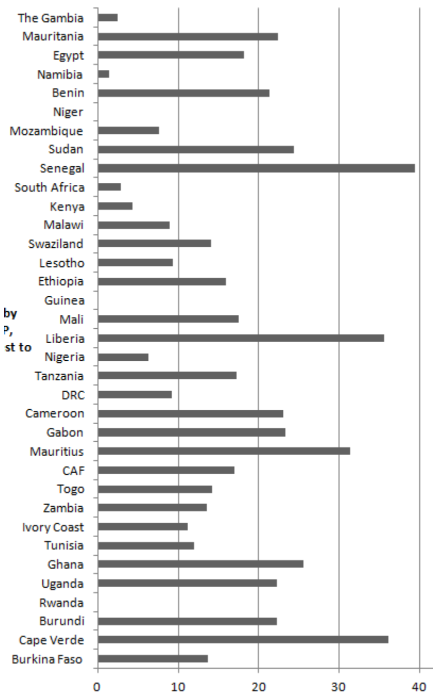
This gives a more accurate impression of resource exploitation and allows to calculate the extraction of non-renewable freshwater in several countries. The table reveals that not only Egypt and Libya, but also South Africa extracts more than its total exploitable resources even including desalination. The values given here do not reflect inter-annual variability, which suggests that South Africa extracts large amounts from deep fossil aquifers consuming large amounts of energy for pumping. Further, FAO (2016) includes irregular flow into the exploitable amount. Considering seasonal dry periods, Algeria and Tunisia can be expected to face similar conditions as South Africa.



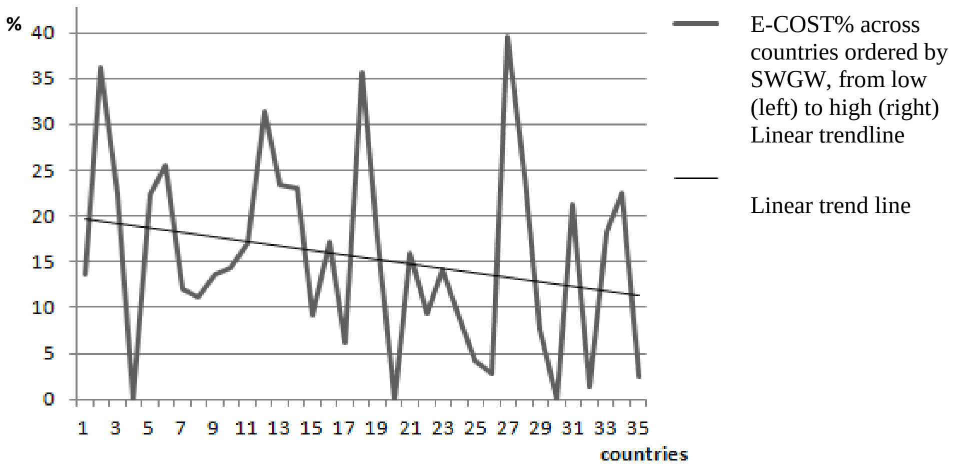
These figures illustrate the shares (%) of exploitable renewable, seawater desalination and the remainder as non-renewable sources in the freshwater portfolios of Egypt, Libya and South Africa. Data for total abstraction: World Bank (2016) for 2014. Data for total renewable freshwater, desalination and exploitable water: FAO (2016) with latest available values (since 2005).

South Africa uses an average 4% non-renewable freshwater and 0.001% desalinated seawater, or 2 million m^3. Egypt can cover 73% of water withdrawal with renewable resources, uses 0.002% seawater, or 20 million m^3 (ten times the amount of South Africa), and more than a quarter non-renewable. Libya displays the highest disparity between availability and use, with only 15% of demand covered by renewable and 85% with non-renewable resources. Seawater provides 0.004%, or 2 million m^3.

Annex 4



This figure ranks the countries with available E-COST% values from largest to smallest SWGWDEP. E-COST% data: IBNET (2015), data on renewable surface and groundwater: FAO (2016)



Above figure shows a linear downward trend in electricity costs when ranking countries from relative groundwater to surface water dependency.

Annex 5

The following map showcases regionally concentrated population densities.

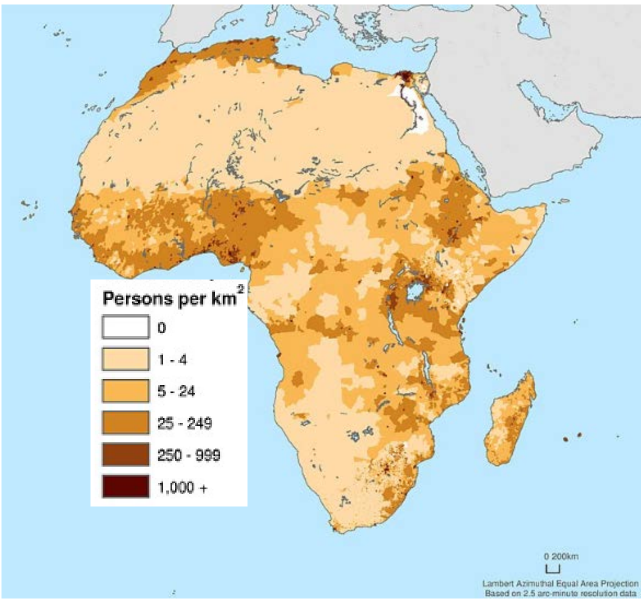


Figure 12 displays population densities across the African continent. Data and map: CIESIN and CIAT (2005)

Annex 6

Country Code	ABSTAGRI	VAAGRIGROW	ABSTIND	VAINDGROW	POPDENS	POPGROW
AGO	20.78		33.95		19.4333232	3.26955241
BDI	77.08	3.349214883	5.903	7.951551451	421.21729	3.29780375
BEN	45.38	5.117085863	23.08	7.24132927	93.9915041	2.64107676
BFA	51.43	2.118417096	2.653	6.197639908	64.2880044	2.91101832
BWA	41.24	-0.34851709	18.04	2.894590159	3.91709809	1.97561406
CAF	0.5517	1.000000004	16.55	1.000000003	7.71183024	1.96828339
CIV	38.43	11.36944202	20.53	4.055495929	69.6764371	2.44243261
CMR	76.26	4.65503663	7.067	6.794790878	48.1754437	2.49811031
COD	10.52	3.2	21.47	9.2	33.0283981	3.15317545
COG	8.696	8.069057103	21.74	5.680744726	13.1916896	2.48634721
COM	47	2.000000055	5	-0.64275759	413.751209	2.40455092
CPV	90.91	-5.74282762	1.818	1.878885046	127.520099	1.30206195
DJI	15.79	4.299998629	0	3.680465167	37.7987058	1.33509343
DZA	59.23	2.499999881	4.926	3.399999981	16.3470127	1.94039918
EGY	86.38	3.006433431	5.857	1.523668854	89.9891205	2.2188633
ERI	94.5	3.600002299	0.1718	-0.24226238	50.5984554	2.20836041
ETH	93.63	5.446729291	0.3778	17.04233384	96.958732	2.50680866
GAB	28.97	9.688036192	10.14	0.609628953	6.5497458	2.23626645
GHA	66.4	4.649484079	9.674	0.783686756	117.722589	2.35007566
GIN	52.94	2.091439689	9.416	-3.51914414	49.9573783	2.69829437
GMB	43.31	-7.24497859	19.23	2.65714304	190.533696	3.23199269
GNB	82.29	3.300020295	4.571	1.900413058	64.029623	2.43852752
GNQ	5.747		14.94		29.2650624	2.94254672
KEN	59.26	3.455075204	3.884	6.513509566	78.8269723	2.6441214
LBR	9.404	-0.62609823	36.24	10.8048436	45.6452865	2.36740834
LBY	82.85		3.051		3.55717062	-0.1118246
LSO	8.676	4.761904762	45.66	0.622591165	69.472892	1.24688598
MAR	87.79	-2.58409811	2.033	1.712398103	76.0053843	1.39081938
MDG	97.76	3.256718619	0.7927	8.509782654	40.5151478	2.78386974
MLI	97.86	10.38057848	0.0771	9.144456525	14.0027553	2.93342047
MOZ	78.04	3.115022252	2.748	11.04932697	34.609573	2.79097018
MRT	90.59	7.305917647	2.356	4.429454772	3.85138741	2.47238251
MUS	67.72	3.9	2.759	-0.12914895	621.149754	0.18106147
MWI	85.92	6.109571235	3.515	4.843592604	177.081597	3.07228773
NAM	69.79	4.626175994	4.861	3.324901643	2.91860462	2.36947994
NER	66.74	8.960591779	3.325	-0.24345802	15.0893882	4.02943652
NGA	53.75	4.270127449	14.99	7.017945994	194.863671	2.66048733
RWA	68	5.263157895	8	5.783866058	459.730199	2.35027091
SDN	96.21	2.639558058	0.2785	6.686309427	21.5746877	2.14526956
SEN	92.98	3.553724955	2.611	2.862208738	76.2091986	3.12562498
SLE	21.54	0.803679467	26.15	13.81639755	87.4982959	2.18934117
SOM	99.48		0.0606		16.765341	2.39995438
SSD	36.47		34.19		17.9	3.91553649
SWZ	96.55	-1.34362571	1.152	3.340289756	73.7855814	1.46612234
TCD	76.42		11.79		10.7902263	3.30159509
TGO	44.97	14.88369342	2.367	3.923681901	130.817485	2.6553193
TUN	80	2.814906827	4.992	-1.14581404	70.7814109	1.00626446
TZA	89.35	3.38246197	0.4823	10.34298121	58.5037492	3.15436943
UGA	40.66	3.017416746	7.849	3.93900782	188.42495	3.25376537
ZAF	62.69	5.566640518	6.048	-0.07603435	44.5160318	1.57611958
ZMB	73.28	6.499999391	8.27	3.501088692	21.1481766	3.06964015
ZWE	78.91	23.01474705	7.087	-1.98115337	39.4102495	2.30745118

Annex 7

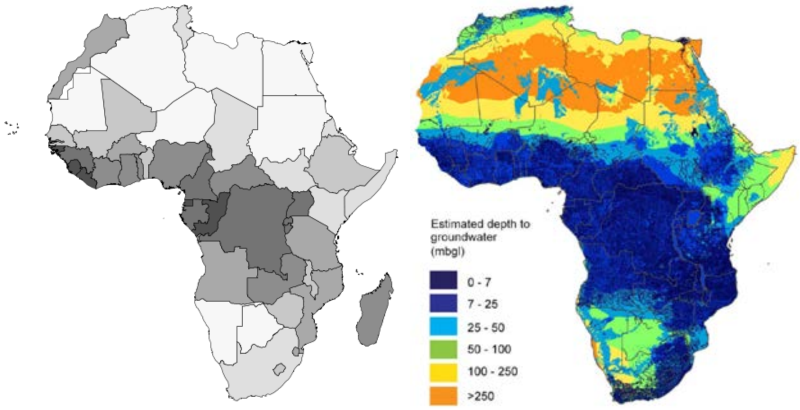


Figure 21 displays total annual renewable groundwater per land area (m^3/km^2) (left) and estimated depth to groundwater (mbgl) (right). Data on renewable groundwater: FAO (2016); land area: The World Factbook (CIA 2014); mapping tool: CartoDB attribution; depth to groundwater: British Geological Survey © NERC (2011), permission granted to modify and publish, see http://www.nationalarchives.gov.uk/doc/open-government-licence/version/3/.

This value is useful, because there is no country-level data on average groundwater tables and the regional distribution of renewable groundwater over land area (m^3/km^2) comes quite close to the estimates modeled by NERC (2011) as displayed above. Absolute and per capita renewable resources are distorted by the size of the country and population sizes, respectively. Further, as the annual renewable volume of groundwater per unit land area is used, fossil aquifers are excluded, therefore excluding groundwater located so deep that human pollution does not reach it.

Morocco stands out as a groundwater-rich country in North Africa. As previously indicated, it has a high groundwater dependency ratio. Therefore, an impact on its groundwater resources may strongly influence energy intensity of drinking water purification in this country.

Annex 8

Country Code	TOTRENCAP	Annual freshwater withdrawals, domestic (% of total freshwater withdrawal)	Annual freshwater withdrawals, total (billion cubic meters)	RENSW	RENGW	GDPCAPGROW	ACCIWS
AGO	5931	17.01	0.288	145.4	58	6.65606131	49
BDI	1122	82.9	0.0725	12.54	7.47	1.265698051	75.9
BEN	2426	31.54	0.13	26.09	1.8	3.764477105	77.9
BFA	745.6	40.72	0.194	9	9.5	1.012339607	82.3
BWA	5411	45.92	0.818	10.64	1.7	2.378328495	96.2
CAF	28776	69.57	0.046	141	56	-0.958401737	68.5
CIV	3706	36.86	3.218	81.3	37.84	5.927408107	81.9
CMR	12127	41.05	1.549	278.1	100	3.313571167	75.6
COD	16605	84.21	0.019	1282	421	5.661810221	52.4
COG	180087	3.528	26.93	832	122	4.157754283	76.5
COM	1522	7.273	0.022	0.2	1	-0.36321437	90.1
CPV	576.4	16.67	0.9664	0.181	0.124	1.470005584	91.7
DJI	337.9	35.85	8.425	0.3	0.015	4.59439792	90
DZA	294.2	45.27	0.7058	10.15	1.517	1.805280999	83.6
EGY	637.1	7.76	68.3	56	2.3	-0.014545788	99.4
ERI	1399	5.991	5.558	7.215	0.5	6.41288427	57.8
ETH	1227	60.89	0.1391	120	20	7.549061296	57.3
GAB	96232	23.93	0.982	164	62	2.00800853	93.2
GHA	2050	37.46	0.0905	54.9	26.3	1.570610426	88.7
GIN	17924	13.14	0.175	226	38	-2.272865867	76.8
GMB	4018	37.65	0.5533	25	0.5	-2.330767488	90.2
GNB	17028	79.31	0.0174	27.4	14	0.070054246	79.3
GNQ	30766	5.326	0.582	25	10	-3.19495214	47.9
KEN	666.7	54.36	0.1308	30.2	3.5	2.579553104	63.2
LBR	51521	45.66	0.0438	232	45	-1.654867373	75.6
LBY	111.5	10.19	10.43	0.2	0.6	-23.91496575	96.6
LSO	1415	14.1	4.326	3.022	0.5	2.35484469	81.8
MAR	843.6	10.55	1.357	22	10	1	85.4
MDG	15544	1.447	16.5	332	55	0.479267903	51.5
MLI	6818	19.22	0.8842	110	20	4.095838066	77
MOZ	7760	25.35	0.288	214.1	17	4.3	51.1
MRT	2802	7.067	1.35	11.1	0.3	3.820065624	57.9
MUS	2161	29.52	0.725	2.358	0.893	3.412590032	99.9
MWI	15544	2.063	5.186	17.28	2.5	2.501969765	90.2
NAM	16230	29.93	0.9836	37.85	2.1	3.881444901	91
NER	1711	31.27	13.11	31.55	2.5	2.678176028	58.2
NGA	1571	24	0.15	279.2	87	3.518654246	68.5
RWA	1146	4.412	2.221	13.3	7	4.478851004	76.1
SDN	939.5	52.66	0.169	35.8	3	0.91178284	55.5
SEN	2576	52.31	0.2122	36.97	3.5	1.497992978	78.5
SLE	24795	0.4548	3.298	150	25	2.344717677	62.6
SOM	1363	29.33	0.658	14.4	3.3	0.07	31.7
SSD	4011	11.79	0.8796	49.5	4	-0.59576559	58.7
SWZ	3504	15.01	3.305	4.51	0.66	0.959282012	74.1
TCD	3256	48	0.01	44.2	11.5	3.815232175	50.8
TGO	2012	51.49	0.637	14	5.7	2.938916505	63.1
TUN	410.1	31.23	12.5	3.42	1.595	1.667623689	97.7
TZA	1800	10.17	5.184	92.27	30	3.649233605	55.6
UGA	1540	68.01	0.6836	60.1	29	1.459717048	79
ZAF	942.4	2.303	1.042	49.55	4.8	-0.039281199	93.2
ZMB	6464	18.45	1.572	104.8	47	2.795614669	65.4
ZWE	1282	14.01	4.205	19	6	1.479476026	76.9

Country Code	ACCSAN	WWTREATNEW	URBPOPGROW	RENGW	LOSSES %	AGRIDRIVER	INDDRIVER
AGO	51.6	34.63992	5.097879089	58		0.17712842	0.734918706
BDI	48	0	5.785764863	7.47		0.45374404	0.358760795
BEN	19.7	0.0084	3.629524833	1.8	23.26	0.29958453	0.64677351
BFA	19.7	0.95	5.84079712	9.5		0.30005794	0.248519064
BWA	63.4	0.025	2.411970355	1.7	18.76	0.20878915	0.417427203
CAF	21.8	0	2.621829122	56	39.95	0	0.327640833
CIV	22.5	0	3.78463208	37.84		0.34128292	0.500272202
CMR	45.8	19.4	3.560982125	100	33.34	0.46396121	0.340373386
COD	28.7	0	4.387654094	421	51.16	0.08273052	0.679436497
COG	15	0	3.144308419	122		0.13402767	0.571807168
COM	35.8	1.444705	2.720897363	1		0.26951382	0.065624752
CPV	72.2	0	2.407991143	0.124		0.41982491	0.09697086
DJI	47.4	0	1.433521664	0.015	41.34	0.13121709	0.12006559
DZA	87.6	49.49814	2.826978113	1.517	27.91	0.40629291	0.289613774
EGY	94.7	1.25	2.321077906	2.3		0.60214047	0.307169441
ERI	15.7	0	4.155753682	0.5		0.55799436	0
ETH	28	0	4.835587363	20	23.44	0.57348059	0.551648932
GAB	41.9	0	2.538134776	62	22.81	0.26634593	0.198349952
GHA	14.9	0.4	3.588229423	26.3	17.41	0.41074404	0.197658734
GIN	20.1	10.24839	3.990686259	38	51.55	0.30291282	0.053398574
GMB	58.9	0.751111	4.325799975	0.5	30.92	0.13283982	0.430920653
GNB	20.8	0	4.106278147	14	45.00	0.48032666	0.138720417
GNQ	74.5	0.6	3.32824609	10	23.89	0.10649685	0.116119612
KEN	30.1	0.519794	4.312926867	3.5	41.77	0.36401011	0.287014225
LBR	16.9	0.3	3.155377194	45	28.80	0.02832875	1
LBY	96.6	0	0.129659509	0.6	48.97	1	0.59425361
LSO	30.3	18.08383	3.199484612	0.5		0.09348783	0.848147735
MAR	76.7	0.53125	2.2	10	33.52	0.46773009	0.134134703
MDG	12	0	4.646296606	55	36.36	0.56894575	0.286942236
MLI	24.7	0	4.946244634	20	27.74	0.65882467	0.293409081
MOZ	20.5	0	3.6	17	37.91	0.45441789	0.397714297
MRT	40	5.438889	3.522501813	0.3	54.37	0.58659071	0.194376633
MUS	93.1	39.39325	-0.23258485	0.893		0.43030206	0.0755619
MWI	41	2.5	4.058379657	2.5	37.83	0.54222176	0.223369847
NAM	34.4	13	4.580740065	2.1	14.20	0.42824394	0.189759976
NER	10.9	0	5.386795578	2.5	12.43	0.46799205	0.050620216
NGA	29	1.081716	4.483488091	87	40.68	0.33868358	0.497655844
RWA	61.6	0.18	5.903928991	7		0.42676140	0.326129112
SDN	24	0	2.631236832	3	40.97	0.61119869	0.308649479
SEN	47.6	2.0625	3.851884295	3.5	19.99	0.54703337	0.1406569
SLE	13.3	0	3.082718161	25		0.11336938	0.912417254
SOM	23.5	0	3.599612233	3.3		0.35333091	0.02521878
SSD	6.7	27.85875	5.002565889	4	26.77	0.21993240	0.832700012
SWZ	57.5	0	1.362980754	0.66		0.52033716	0.152783213
TCD	12.1	0	3.813200361	11.5	8.65	0.75371609	0.403204113
TGO	11.6	55.5	3.904595977	5.7	40.00	0.42106375	0.164008903
TUN	91.6	0.425	1.290264639	1.595	55.50	0.52432161	0.144737136
TZA	15.6	0	5.462279902	30	13.97	0.52457265	0.340536966
UGA	19.1	27.7731	5.362607218	29	25.95	0.24757188	0.264316971
ZAF	66.4	0.56	2.372463674	4.8	35.11	0.42179709	0.134510329
ZMB	43.9	4.2	4.175253604	47	51.16	0.47181204	0.258587394
ZWE	36.8	14.03196	1.837793497	6		0.72836571	0.088088921

Country Code	AGRIDRIVER	INDDRIVER	TOTRENCAP-DRIVER	GWDEPDRIVER	Cumulative stage 1	POPDENS-DRIVER
AGO	0.177128422	0.734918706	0.967665043	0.865886722	2.745598894	0.561869974
BDI	0.453744042	0.358760795	0.994385347	0.428099953	2.234990137	1
BEN	0.299584528	0.64677351	0.987139916	0.708513481	2.642011435	0.541081257
BFA	0.300057943	0.248519064	0.996476743	0.918715548	2.463769298	0.552514596
BWA	0.20878915	0.417427203	0.970554325	0.886123511	2.48289419	0.336673323
CAF	0	0.327640833	0.8407311	0.777157175	1.945529107	0.339587382
CIV	0.34128292	0.500272202	0.980027837	0.727876902	2.54945986	0.482840607
CMR	0.463961213	0.340373386	0.933238135	0.526467527	2.26404026	0.468607791
COD	0.08273052	0.679436497	0.908356971	0.5844797	2.255003688	0.557792636
COG	0.134027668	0.571807168	0	0.153598932	0.859433767	0.428960605
COM	0.269513819	0.065624752	0.992162822	0.089772223	1.417073616	0.848040692
CPV	0.41982491	0.09697086	0.997416871	0.917286714	2.431499354	0.361548754
DJI	0.131217085	0.12006559	0.998742051	0.638910123	1.888934849	0.270048694
DZA	0.406292908	0.289613774	0.998984862	0.882870565	2.57776211	0.344413776
EGY	0.602140466	0.307169441	0.997079603	0.555851236	2.462240745	0.468743856
ERI	0.557994358	0	0.992846249	0.733641994	2.284482601	0.42454404
ETH	0.573480588	0.551648932	0.993801934	0.859861566	2.97879302	0.522652797
GAB	0.266345925	0.198349952	0.465924529	0.485476751	1.416097158	0.381505221
GHA	0.410744035	0.197658734	0.98922909	0.74346857	2.341100428	0.519810206
GIN	0.302912818	0.053398574	0.901028196	0.58227961	1.839619198	0.502780251
GMB	0.132839815	0.430920653	0.978294268	0	1.542054736	0.740459366
GNB	0.48032666	0.138720417	0.906006651	0.179811821	1.704865549	0.476117831
GNQ	0.106496853	0.116119612	0.829674039	0.233246095	1.2855366	0.519799351
KEN	0.364010108	0.287014225	0.996915136	0.836343597	2.484283066	0.525207184
LBR	0.028328746	1	0.714352787	0.08746746	1.830148993	0.444821416
LBY	1	0.59425361	1	1	3.59425361	0
LSO	0.093487829	0.848147735	0.992757348	0.862401467	2.796794379	0.290019227
MAR	0.467730092	0.134134703	0.995932224	0.920767964	2.518564983	0.320256232
MDG	0.568945754	0.286942236	0.914252218	0.704909438	2.475049645	0.50637695
MLI	0.658824674	0.293409081	0.962736595	0.873077042	2.788047392	0.501859043
MOZ	0.454417889	0.397714297	0.957502549	0.732557909	2.542192644	0.50114792
MRT	0.586590707	0.194376633	0.985050743	0.328046442	2.094064526	0.416631463
MUS	0.430302059	0.0755619	0.988612339	0.064805141	1.55928144	0.713648923
MWI	0.542221759	0.223369847	0.914250659	0.837044293	2.516886559	0.700214391
NAM	0.428243943	0.189759976	0.910440588	0.671250456	2.199694962	0.399047333
NER	0.467992051	0.050620216	0.991112679	0.771468447	2.281193393	0.679599085
NGA	0.338683581	0.497655844	0.991890563	0.755729212	2.5839592	0.653062876
RWA	0.426761402	0.326129112	0.994251995	0.429432674	2.176575184	0.888913713
SDN	0.611198689	0.308649479	0.995399374	0.784792268	2.700039811	0.383059612
SEN	0.547033367	0.1406569	0.986306469	0.776881982	2.450878719	0.599952146
SLE	0.113369379	0.912417254	0.862850777	0.185452703	2.074090112	0.461299927
SOM	0.353330908	0.02521878	0.993046276	0.916261018	2.287856982	0.41889923
SSD	0.219932401	0.832700012	0.978333162	0.767314088	2.798279663	0.664282898
SWZ	0.520337163	0.152783213	0.981150212	0.803966925	2.458237514	0.329992022
TCD	0.753716091	0.403204113	0.982528177	0.918076051	3.057524432	0.557704968
TGO	0.421063749	0.164008903	0.989440229	0.756877036	2.331389917	0.58311589
TUN	0.52432161	0.144737136	0.998340885	0.947604146	2.615003778	0.252667336
TZA	0.524572649	0.340536966	0.990618167	0.885784195	2.741511978	0.585476303
UGA	0.247571882	0.264316971	0.992062809	0.72321674	2.227168401	0.74169131
ZAF	0.421797087	0.134510329	0.99538326	0.809561527	2.361252203	0.316126733
ZMB	0.471812038	0.258587394	0.964703529	0.83845512	2.533558081	0.531514807
ZWE	0.728365709	0.088088921	0.993496337	0.917419589	2.727370555	0.428433919

Country Code	WWDRIVER	WQAGRI	WQIND	Cumulative stage 2	URBPOP-DRIVER	CAPDEM-DRIVER	Cumulative volume
AGO	0.389690665	0.439189635	0.673531212	2.064281487	0.875815783	0.946079488	1.82189527
BDI	0.383256484	0.868210071	0.411497658	2.662964212	0.939864492	0.653635528	1.593500019
BEN	0.626729915	0.403478665	0.748446391	2.319736228	0.665204746	0.713732218	1.378936964
BFA	0.450579472	0.532428702	0.326345671	1.861868441	0.894391289	0.561178933	1.455570222
BWA	0.428316008	0.389982986	0.502422958	1.657395274	0.471795609	0.494394208	0.966189816
CAF	0.463603548	0.34335738	0.402103652	1.548651962	0.489261144	0.712431762	1.201692906
CIV	0.452438908	0.635041899	0.51163493	2.081956344	0.652983612	0.665803074	1.318786686
CMR	0.400992602	0.813298079	0.413280894	2.096179365	0.64059541	0.696720125	1.337315535
COD	0.447158324	0.487448605	0.642873441	2.135273006	0.798345246	0.913437591	1.711782837
COG	0.543353663	0.66235326	0.613179003	2.247846532	0.602494868	0.727829337	1.330324205
COM	0.379275734	0.908211011	0.200589794	2.33611723	0.554694851	0.543015652	1.097710503
CPV	0.184930522	0.616138538	0.229731597	1.392349411	0.383847707	0.571031808	0.954879515
DJI	0.622215993	0.208199504	0.452964276	1.553428466	0.302616189	0.631210384	0.933826573
DZA	0.083882483	0.488664176	0.358405722	1.275366157	0.503640226	0.520421646	1.024061872
EGY	0.157029863	0.461365448	0.526749875	1.613889041	0.495453864	0.343972858	0.839426722
ERI	0.640751477	0.587654009	0.309177089	1.962126616	0.65511408	0.881404533	1.536518613
ETH	0.487798677	0.68644733	0.586479942	2.283378746	0.753596464	0.914113819	1.667710282
GAB	0.406595203	0.681933184	0.317170314	1.787203921	0.516767914	0.515817203	1.032585117
GHA	0.41958586	0.682638687	0.308988609	1.931023362	0.623734247	0.590741332	1.214475578
GIN	0.509433156	0.609395998	0.257097583	1.878706988	0.704344652	0.581611635	1.285956288
GMB	1	0	1	2.740459366	0.803166979	0.501919811	1.30508679
GNB	0.459887523	1	0.269252584	2.205257937	0.680706029	0.624136974	1.304843003
GNQ	0.394459681	0.677403991	0.260661892	1.852324915	0.677969659	0.783591034	1.461560693
KEN	0.511831866	0.486776679	0.433794234	1.957609962	0.725581673	0.689055518	1.414637191
LBR	0.515736796	0.639361262	0.880457289	2.480376764	0.587997788	0.616168895	1.204166683
LBY	0.240007447	0.628650681	0	0.868658128	0	0	0
LSO	0.479105735	0.315533484	0.787730996	1.872389442	0.446139757	0.631366163	1.077505921
MAR	0	0.619476109	0.237057685	1.176790027	0.377136027	0.563211567	0.940347594
MDG	0.542394486	0.753716856	0.409840218	2.21232851	0.773015867	0.830856388	1.603872255
MLI	0.492258251	0.754956	0.408688723	2.157762018	0.818791545	0.717190371	1.535981916
MOZ	0.583045743	0.54433486	0.56102323	2.189551753	0.682107757	0.906154719	1.588262476
MRT	0.857193999	0.412155971	0.687349289	2.373330722	0.63387204	0.823805224	1.457677264
MUS	0.427916711	0.985291077	0.211510087	2.338366798	0.006297698	0.052894664	0.059192362
MWI	0.463968034	0.655121538	0.374507277	2.193811239	0.758925593	0.550973217	1.309898809
NAM	0.533980623	0.460218922	0.482489927	1.875736805	0.713368725	0.551340339	1.264709064
NER	0.635527683	0.534711493	0.327332646	2.177170907	1	0.752770598	1.752770598
NGA	0.441096835	0.600314886	0.519261466	2.213736063	0.742679991	0.731051049	1.473731039
RWA	0.37898801	0.843780363	0.393230871	2.504912957	0.827004393	0.735316213	1.562320606
SDN	0.578259553	0.604243749	0.430477323	1.996040238	0.513104735	0.758201408	1.271306142
SEN	0.483448132	0.62625963	0.361962651	2.071622559	0.747738633	0.66561553	1.413354163
SLE	0.540297633	0.645459097	0.831335613	2.47839227	0.558462155	0.761335724	1.319797879
SOM	0.481620951	0.505685322	0.200651251	1.606856753	0.63122026	1	1.63122026
SSD	0.64859327	0.350056014	0.848179988	2.51111217	0.951463617	0.692618051	1.644081669
SWZ	0.134231498	0.644411276	0.312784271	1.421419067	0.313465874	0.602561756	0.91602763
TCD	0.51686412	0.837228108	0.465665224	2.377462421	0.767229163	0.883360953	1.650590115
TGO	0.500755268	0.678580542	0.291173409	2.053625109	0.691199552	0.78216204	1.473361592
TUN	0.111290849	0.627433673	0.211454179	1.202846038	0.247277008	0.465632299	0.712909308
TZA	0.490881046	0.685635978	0.412142915	2.174136243	0.892818488	0.846992643	1.739811131
UGA	0.463958232	0.566564447	0.353945381	2.126159371	0.896997312	0.614400283	1.511397595
ZAF	0.226159553	0.505662732	0.338414387	1.386363405	0.416372023	0.418563689	0.834935712
ZMB	0.365645551	0.683705497	0.351480381	1.932346235	0.768839078	0.746579281	1.515418358
ZWE	0.325470221	0.816359521	0.230538376	1.800802037	0.464558141	0.554584415	1.019142556

Annex 9

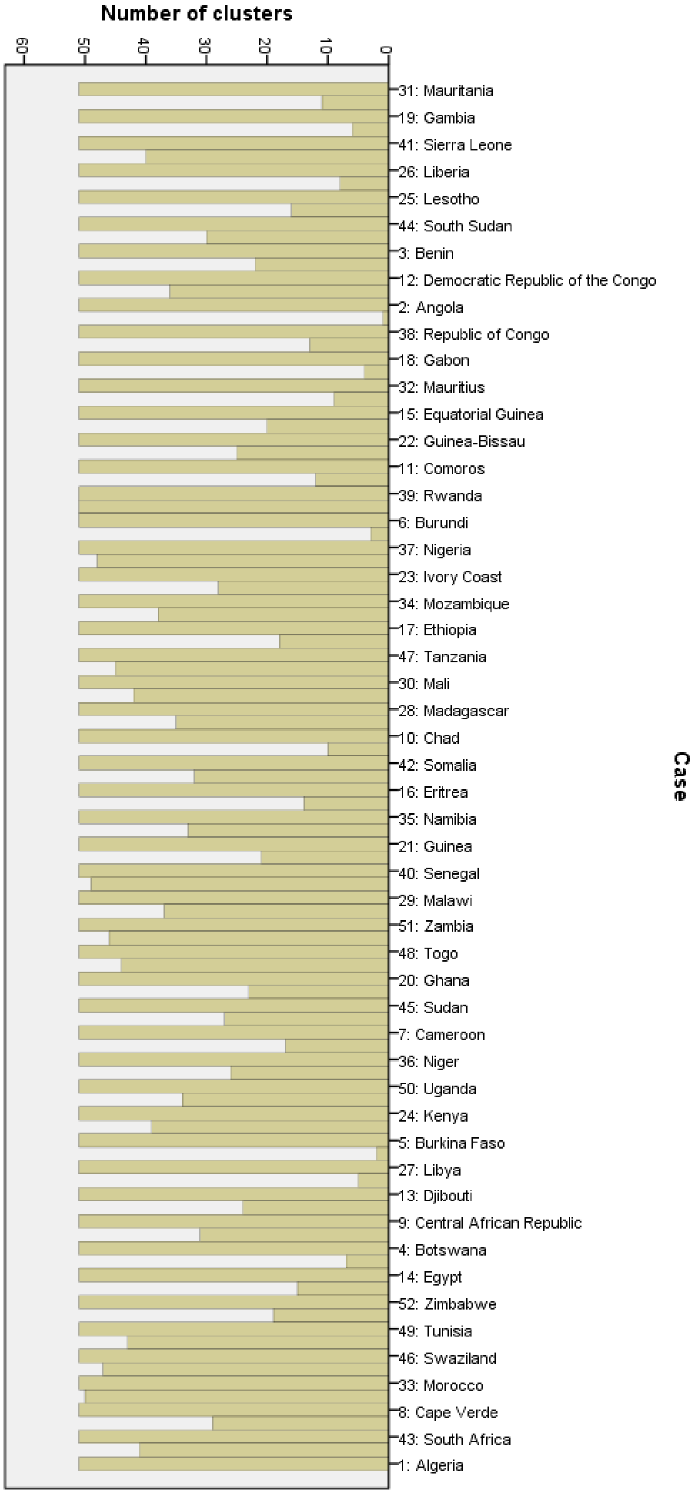
order if coeff: (multiplied a(WQ) with the sum of rescaled ACCSAN and WWTREATNEW values; sumof2*a(WQ))	WWTREATNEW	ACCSAN	order if sum: (z(ACCSAN)+ z(WWTREATNEW)+ z(a(WQ))	WWTREATNEW	ACCSAN
	49.49814	94.70		49.49814	94.70
	39.39325	76.70		39.39325	76.70
	34.63992	87.60		34.63992	87.60
	55.5	57.50		55.5	57.50
	27.7731	91.60		27.7731	91.60
	27.85875	66.40		27.85875	66.40
	19.4	72.20		19.4	72.20
	18.08383	96.60		18.08383	96.60
	14.03196	36.80		14.03196	36.80
	13	34.40		13	34.40
	4.2	43.90		4.2	43.90
	2.0625	47.60		2.0625	47.60
	0.95	63.40		5.438889	93.10
	0.4	58.90		0.95	63.40
	0	61.60		10.24839	14.90
	0	51.60		1.444705	35.80
	0	48.00		0.4	58.90
	1.25	74.50		0	51.60
	0	47.40		0	48.00
	0	45.80		0	47.40
	0	41.90		0	45.80
	0	41.00		1.25	74.50
	0	40.00		0	41.90
	1.444705	35.80		0	61.60
	10.24839	14.90		0	41.00
	5.438889	93.10		0	40.00
	1.081716	29.00		1.081716	29.00
	0.519794	30.10		0.519794	30.10
	0.3	30.30		0.3	30.30
	0	28.70		2.5	20.50
	0	28.00		0	28.70
	2.5	20.50		0	28.00
	0	24.70		0	24.70
	0	24.00		0.6	22.50
	0.6	22.50		0	24.00
	0	23.50		0	23.50
	0	21.80		0.751111	20.10
	0.751111	20.10		0	21.80
	0	20.80		0	20.80
	0.56	19.10		0.56	19.10
	0.025	19.70		0.025	19.70
	0.0084	19.70		0.0084	19.70
	0	16.90		0	16.90
	0.425	15.60		0.425	15.60
	0	15.70		0	15.70
	0.18	15.00		0.18	15.00
	0	13.30		0	13.30
	0.53125	12.00		0.53125	12.00
	0	12.10		0	12.10
	0	11.60		0	11.60
	0	10.90		0	10.90
	0	6.70		0	6.70

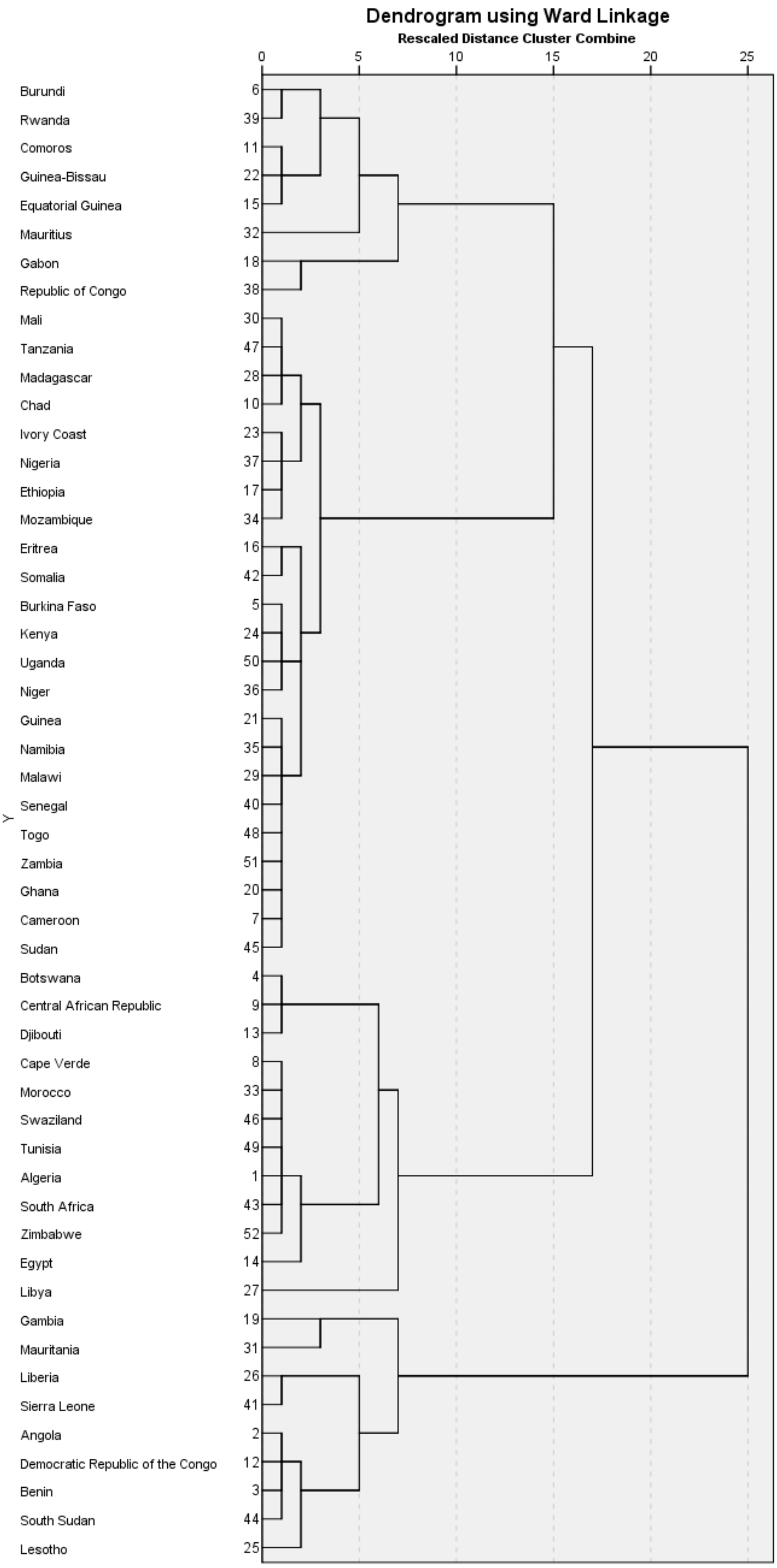
Annex 10

Ward Linkage (Squared Eucledian Distance)

Agglomeration Schedule

Stage	Cluster Combined		Coefficients	Stage Cluster First Appears		Next Stage
	Cluster 1	Cluster 2		Cluster 1	Cluster 2	
1	6	39	.017	0	0	40
2	8	33	.037	0	0	5
3	29	40	.057	0	0	15
4	23	37	.079	0	0	24
5	8	46	.103	2	0	9
6	48	51	.128	0	0	8
7	30	47	.156	0	0	10
8	20	48	.187	0	6	15
9	8	49	.219	5	0	23
10	28	30	.253	0	7	17
11	1	43	.287	0	0	23
12	26	41	.323	0	0	44
13	5	24	.361	0	0	18
14	17	34	.407	0	0	24
15	20	29	.460	8	3	29
16	2	12	.515	0	0	30
17	10	28	.570	0	10	34
18	5	50	.626	13	0	26
19	21	35	.690	0	0	31
20	16	42	.757	0	0	38
21	4	9	.828	0	0	28
22	3	44	.906	0	0	30
23	1	8	.994	11	9	33
24	17	23	1.088	14	4	34
25	7	45	1.186	0	0	29
26	5	36	1.301	18	0	35
27	11	22	1.423	0	0	32
28	4	13	1.559	21	0	45
29	7	20	1.700	25	15	31
30	2	3	1.849	16	22	36
31	7	21	1.999	29	19	35
32	11	15	2.157	27	0	40
33	1	52	2.326	23	0	37
34	10	17	2.559	17	24	42
35	5	7	2.803	26	31	38
36	2	25	3.060	30	0	44
37	1	14	3.319	33	0	45
38	5	16	3.622	35	20	42
39	18	38	3.945	0	0	48
40	6	11	4.368	1	32	43
41	19	31	4.815	0	0	46
42	5	10	5.349	38	34	49
43	6	32	6.186	40	0	48
44	2	26	7.026	36	12	46
45	1	4	7.945	37	28	47
46	2	19	9.070	44	41	51
47	1	27	10.209	45	0	50
48	6	18	11.390	43	39	49
49	5	6	13.989	42	48	50
50	1	5	16.934	47	49	51
51	1	2	21.370	50	46	0


Number of clusters
60
50
40
30
20
10
0
31: Mauritania
19: Gambia
41: Sierra Leone
26: Liberia
25: Lesotho
44: South Sudan
3: Benin
12: Democratic Republic of the Congo
2: Angola
38: Republic of Congo
18: Gabon
32: Mauritius
15: Equatorial Guinea
22: Guinea-Bissau
11: Comoros
39: Rwanda
6: Burundi
37: Nigeria
23: Ivory Coast
34: Mozambique
17: Ethiopia
47: Tanzania
30: Mali
28: Madagascar
10: Chad
42: Somalia
16: Eritrea
35: Namibia
21: Guinea
40: Senegal
29: Malawi
51: Zambia
48: Togo
20: Ghana
45: Sudan
7: Cameroon
36: Niger
50: Uganda
24: Kenya
5: Burkina Faso
27: Libya
13: Djibouti
9: Central African Republic
4: Botswana
14: Egypt
52: Zimbabwe
49: Tunisia
46: Swaziland
33: Morocco
8: Cape Verde
43: South Africa
1: Algeria
Case

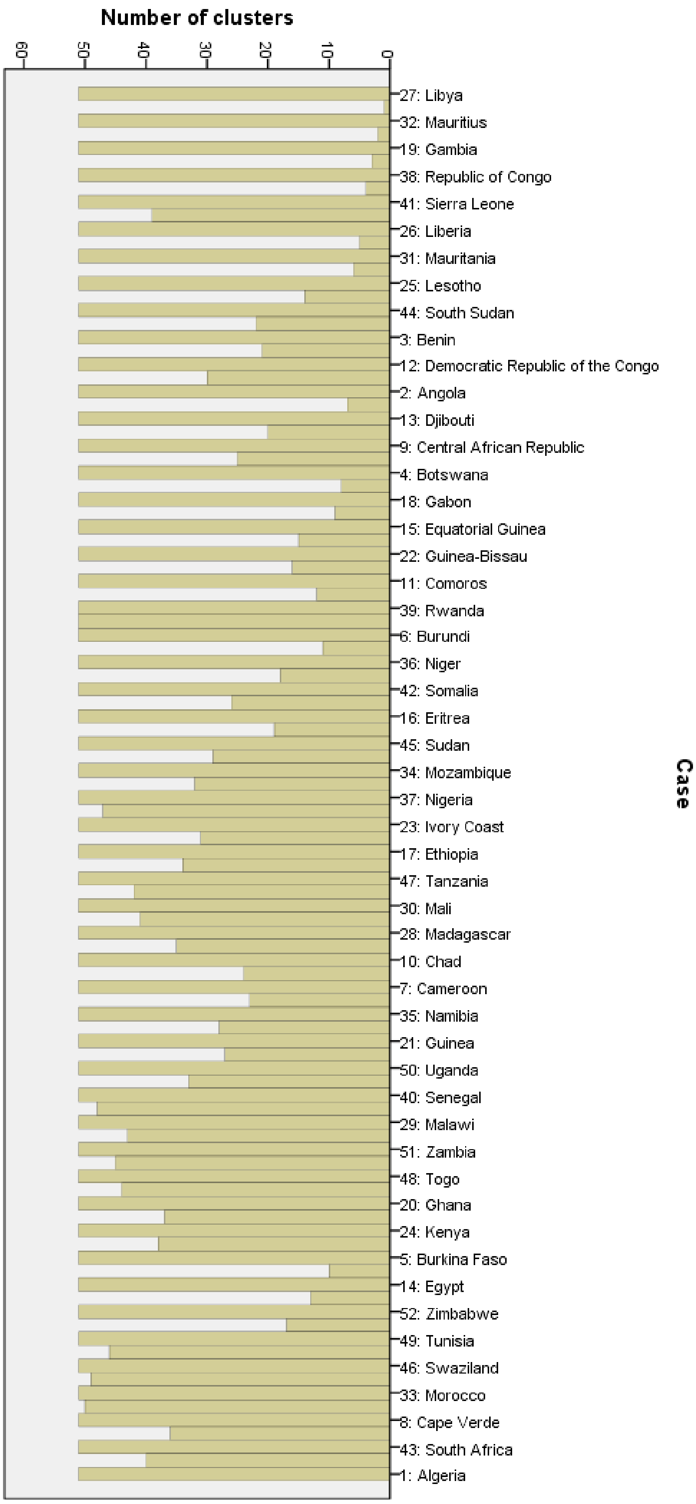


Dendrogram using Ward Linkage
Rescaled Distance Cluster Combine
0
5
10
15
20
25
Y
Burundi 6
Rwanda 39
Comoros 11
Guinea-Bissau 22
Equatorial Guinea 15
Mauritius 32
Gabon 18
Republic of Congo 38
Mali 30
Tanzania 47
Madagascar 28
Chad 10
Ivory Coast 23
Nigeria 37
Ethiopia 17
Mozambique 34
Eritrea 16
Somalia 42
Burkina Faso 5
Kenya 24
Uganda 50
Niger 36
Guinea 21
Namibia 35
Malawi 29
Senegal 40
Togo 48
Zambia 51
Ghana 20
Cameroon 7
Sudan 45
Botswana 4
Central African Republic 9
Djibouti 13
Cape Verde 8
Morocco 33
Swaziland 46
Tunisia 49
Algeria 1
South Africa 43
Zimbabwe 52
Egypt 14
Libya 27
Gambia 19
Mauritania 31
Liberia 26
Sierra Leone 41
Angola 2
Democratic Republic of the Congo 12
Benin 3
South Sudan 44
Lesotho 25

Median Linkage: Squared Eucledian Distance

Agglomeration Schedule

Stage	Cluster Combined		Coefficients	Stage Cluster First Appears		Next Stage
	Cluster 1	Cluster 2		Cluster 1	Cluster 2	
1	6	39	.034	0	0	40
2	8	33	.040	0	0	3
3	8	46	.035	2	0	6
4	29	40	.040	0	0	9
5	23	37	.044	0	0	20
6	8	49	.044	3	0	16
7	48	51	.051	0	0	8
8	20	48	.048	0	7	9
9	20	29	.046	8	4	15
10	30	47	.055	0	0	11
11	28	30	.050	0	10	17
12	1	43	.069	0	0	16
13	26	41	.072	0	0	47
14	5	24	.075	0	0	15
15	5	20	.076	14	9	19
16	1	8	.078	12	6	35
17	10	28	.080	0	11	18
18	10	17	.089	17	0	21
19	5	50	.089	15	0	25
20	23	34	.098	5	0	21
21	10	23	.102	18	20	23
22	2	12	.108	0	0	31
23	10	45	.125	21	0	28
24	21	35	.128	0	0	25
25	5	21	.111	19	24	29
26	16	42	.134	0	0	33
27	4	9	.142	0	0	32
28	7	10	.152	0	23	29
29	5	7	.145	25	28	33
30	3	44	.155	0	0	31
31	2	3	.149	22	30	38
32	4	13	.204	27	0	44
33	5	16	.211	29	26	34
34	5	36	.183	33	0	41
35	1	52	.211	16	0	39
36	11	22	.246	0	0	37
37	11	15	.238	36	0	40
38	2	25	.322	31	0	45
39	1	14	.322	35	0	42
40	6	11	.372	1	37	41
41	5	6	.399	34	40	42
42	1	5	.457	39	41	43
43	1	18	.390	42	0	44
44	1	4	.397	43	32	45
45	1	2	.563	44	38	46
46	1	31	.598	45	0	47
47	1	26	.773	46	13	48
48	1	38	.838	47	0	49
49	1	19	1.221	48	0	50
50	1	32	2.158	49	0	51
51	1	27	2.499	50	0	0


Number of clusters
60
50
40
30
20
10
0
27: Libya
32: Mauritius
19: Gambia
38: Republic of Congo
41: Sierra Leone
26: Liberia
31: Mauritania
25: Lesotho
44: South Sudan
3: Benin
12: Democratic Republic of the Congo
2: Angola
13: Djibouti
9: Central African Republic
4: Botswana
18: Gabon
15: Equatorial Guinea
22: Guinea-Bissau
11: Comoros
39: Rwanda
6: Burundi
36: Niger
42: Somalia
16: Eritrea
45: Sudan
34: Mozambique
37: Nigeria
23: Ivory Coast
17: Ethiopia
47: Tanzania
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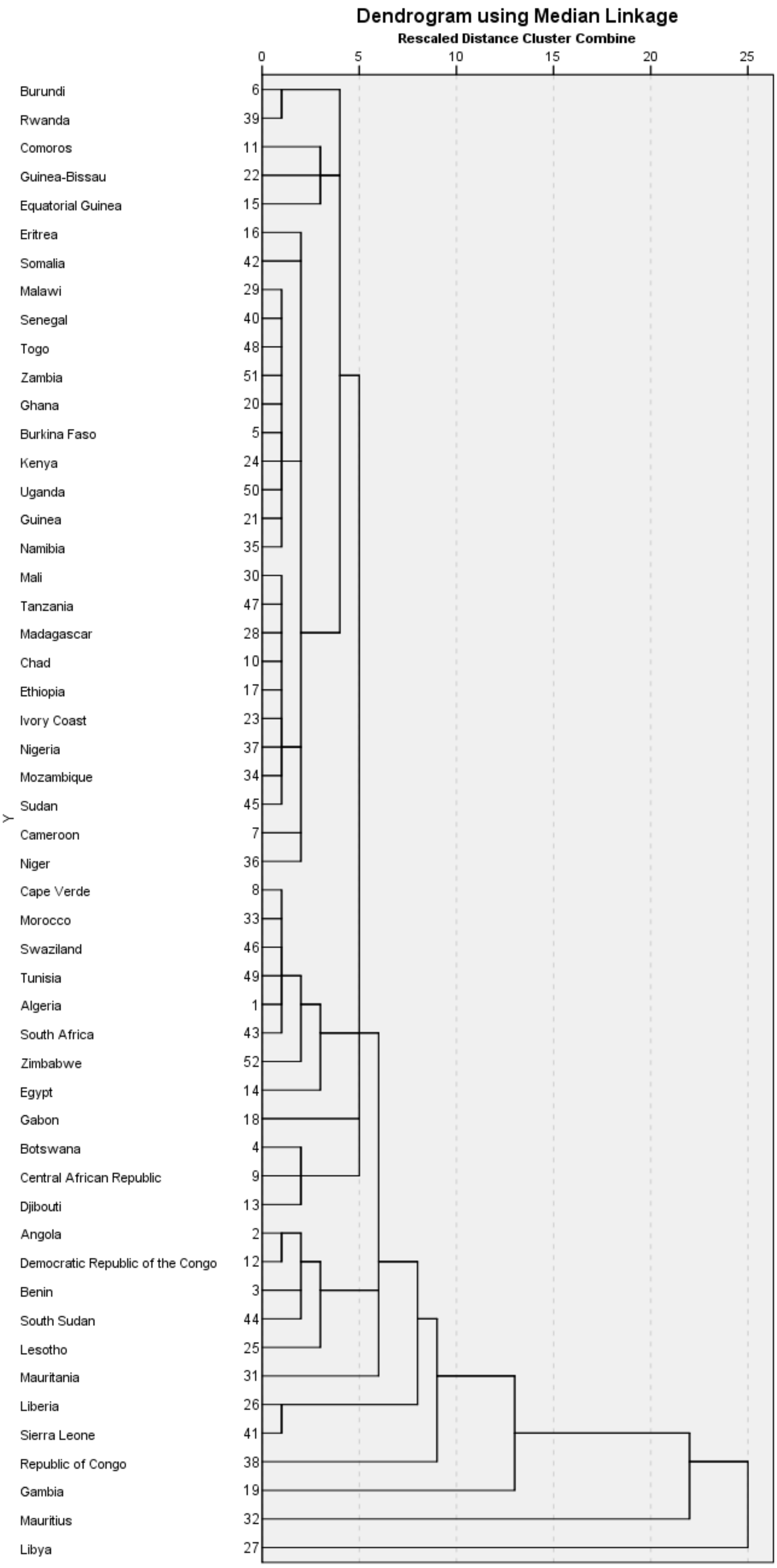
28: Madagascar
10: Chad
7: Cameroon
35: Namibia
21: Guinea
50: Uganda
40: Senegal
29: Malawi
51: Zambia
48: Togo
20: Ghana
24: Kenya
5: Burkina Faso
14: Egypt
52: Zimbabwe
49: Tunisia
46: Swaziland
33: Morocco
8: Cape Verde
43: South Africa
1: Algeria
Case


Dendrogram using Median Linkage
Rescaled Distance Cluster Combine
0
5
10
15
20
25
Y
Burundi 6
Rwanda 39
Comoros 11
Guinea-Bissau 22
Equatorial Guinea 15
Eritrea 16
Somalia 42
Malawi 29
Senegal 40
Togo 48
Zambia 51
Ghana 20
Burkina Faso 5
Kenya 24
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Guinea 21
Namibia 35
Mali 30
Tanzania 47
Madagascar 28
Chad 10
Ethiopia 17
Ivory Coast 23
Nigeria 37
Mozambique 34
Sudan 45
Cameroon 7
Niger 36
Cape Verde 8
Morocco 33
Swaziland 46
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Zimbabwe 52
Egypt 14
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Democratic Republic of the Congo 12
Benin 3
South Sudan 44
Lesotho 25
Mauritania 31
Liberia 26
Sierra Leone 41
Republic of Congo 38
Gambia 19
Mauritius 32
Libya 27

Quick Cluster

```
QUICK CLUSTER AGRIDRIVER INDDRIVER TOTRENCAPDRIVER GWDEPDRIVER POPDENSDRIVER
WWDRIVER WQAGRI WQIND
    URBPOPDRIVER CAPDEMDRIVER
  /MISSING=LISTWISE
  /CRITERIA=CLUSTER(8) MXITER(10) CONVERGE(0)
  /METHOD=KMEANS(NOUPDATE)
  /PRINT ID(Country) INITIAL.
```

Initial Cluster Centers

	Cluster							
	1	2	3	4	5	6	7	8
AGRIDRIVER	.43	.09	.59	.47	.13	.45	.13	1.00
INDDRIVER	.08	.85	.19	.13	.57	.36	.43	.59
TOTRENCAPDRIVER	.99	.99	.99	1.00	.00	.99	.98	1.00
GWDEPDRIVER	.06	.86	.33	.92	.15	.43	.00	1.00
POPDENSDRIVER	.71	.29	.42	.32	.43	1.00	.74	.00
WWDRIVER	.43	.48	.86	.00	.54	.38	1.00	.24
WQAGRI	.99	.32	.41	.62	.66	.87	.00	.63
WQIND	.21	.79	.69	.24	.61	.41	1.00	.00
URBPOPDRIVER	.01	.45	.63	.38	.60	.94	.80	.00
CAPDEMDRIVER	.05	.63	.82	.56	.73	.65	.50	.00

Iteration History[a]

	Change in Cluster Centers							
Iteration	1	2	3	4	5	6	7	8
1	.000	.434	.467	.365	.423	.491	.000	.000
2	.000	.082	.048	.135	.159	.043	.000	.000
3	.000	.000	.064	.102	.000	.012	.000	.000
4	.000	.000	.000	.000	.000	.000	.000	.000

a. Convergence achieved due to no or small change in cluster centers. The maximum absolute coordinate change for any center is .000. The current iteration is 4. The minimum distance between initial centers is .946.

Final Cluster Centers

	Cluster							
	1	2	3	4	5	6	7	8
AGRIDRIVER	.43	.18	.44	.51	.14	.44	.13	1.00
INDDRIVER	.08	.62	.19	.17	.67	.25	.43	.59
TOTRENCAPDRIVER	.99	.95	.98	.99	.51	.96	.98	1.00
GWDEPDRIVER	.06	.77	.71	.84	.23	.66	.00	1.00
POPDENSDRIVER	.71	.47	.42	.35	.43	.62	.74	.00
WWDRIVER	.43	.49	.60	.15	.50	.46	1.00	.24
WQAGRI	.99	.42	.48	.60	.66	.71	.00	.63
WQIND	.21	.64	.44	.31	.66	.37	1.00	.00
URBPOPDRIVER	.01	.67	.61	.40	.57	.77	.80	.00
CAPDEMDRIVER	.05	.72	.78	.50	.66	.71	.50	.00

Number of Cases in each Cluster

Cluster	1	1.000
	2	8.000
	3	8.000
	4	8.000
	5	4.000
	6	21.000
	7	1.000
	8	1.000
Valid		52.000

Cluster Membership

Case Number	Country	Cluster	Distance
1	Algeria	4	.240
2	Angola	2	.367
3	Benin	2	.236
4	Botswana	2	.435
5	Burkina Faso	6	.406
6	Burundi	6	.525
7	Cameroon	6	.283
8	Cape Verde	4	.175
9	CAF	2	.495
10	Chad	6	.499
11	Comoros	6	.767
12	COD	2	.342
13	Djibouti	3	.558
14	Egypt	4	.476
15	GNQ	6	.610
16	Eritrea	3	.312
17	Ethiopia	6	.500
18	Gabon	5	.678
19	Gambia	7	.000
20	Ghana	6	.248
21	Guinea	6	.357
22	Guinea-Bissau	6	.610
23	Ivory Coast	2	.335
24	Kenya	3	.272
25	Lesotho	2	.437
26	Liberia	5	.482
27	Libya	8	.000
28	Madagascar	6	.243
29	Malawi	6	.281
30	Mali	6	.337
31	Mauritania	3	.544
32	Mauritius	1	.000
33	Morocco	4	.206
34	Mozambique	3	.303
35	Namibia	3	.276
36	Niger	6	.423
37	Nigeria	6	.347
38	COG	5	.536
39	Rwanda	6	.402
40	Senegal	6	.220
41	Sierra Leone	5	.477
42	Somalia	3	.450
43	South Africa	4	.185
44	South Sudan	2	.487
45	Sudan	3	.281
46	Swaziland	4	.149
47	Tanzania	6	.326
48	Togo	6	.202
49	Tunisia	4	.241
50	Uganda	6	.326
51	Zambia	6	.228
52	Zimbabwe	4	.393

Distances between Final Cluster Centers

Cluster	1	2	3	4	5	6	7	8
1		1.522	1.321	1.161	1.330	1.225	1.725	1.479
2	1.522		.568	.846	.755	.643	1.157	1.561
3	1.321	.568		.619	.935	.401	1.250	1.439
4	1.161	.846	.619		1.147	.636	1.672	1.042
5	1.330	.755	.935	1.147		.910	1.140	1.740
6	1.225	.643	.401	.636	.910		1.350	1.484
7	1.725	1.157	1.250	1.672	1.140	1.350		2.280
8	1.479	1.561	1.439	1.042	1.740	1.484	2.280	