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Climate Change and Sustainable Development of Water: Sub-Saharan Africa

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1. Introduction

Current scientific consensus predicts that continuing and significant climate changes arising from increasing greenhouse gas emissions will occur in coming decades, likely resulting in widespread alterations to hydrologic conditions. Hydrologic alterations are challenging for sustainable development of water resources, because of the direct reliance on the hydrologic cycle for adequate supplies of water and the cycle's inherent vulnerability to change of temperature, precipitation, and streamflow.

According to the IPCC, African countries are more vulnerable to changes of climate and resultant effects due to lack of capacity and economic development. 200 million people already water-stressed in Africa. Providing access to adequate supplies of water has been a high priority on the agenda of organizations working in the international development community. Progress has been made, but some of the greatest challenges that developing nations continue to face include providing access to water, while successfully managing it as an environmental resource, and mitigating the potential effects of climate change as this resource continues to be developed.

Development and management of water resources has long proceeded under the assumption of a relatively constant climate, subject to some natural fluctuation. Critical water infrastructure in developed countries, such as the Colorado River System, are designed to buffer variability in precipitation and streamflow over time scales of a few years to a decade. Water infrastructure in the developing countries of sub-Saharan Africa is struggling to provide adequate water to inhabitants. Variability in precipitation and streamflow, in the form of a drought, has had devastating consequences.

Access to water affects complex feedback loops between natural resources, land use, hydrologic and climate cycles, policy, population growth, agriculture, socio-economics of development, and stakeholders. The combination of rapid population growth, extreme climate, and uncertainties of inadequate data will have a disproportionate effect on Africa. Already, environmental and human crises have results from inadequate, or mismanaged, access to water in both developed and developing countries. As Sub-Saharan Africa continues to grow, climate change poses uncertainties for resources.

This chapter reviews aspects of population growth, agriculture, and development within the feedback loops; what is known and projected with respect to climate change; hydrologic alterations of surface water and groundwater; caveats; and planning and the path forward.

2. Feedback loops

2.1 Population growth

Sub-Saharan Africa has some of the highest growth rates in the world ranging from 1.6 to 3.1 % per year (Taylor et al., 2009). The population is expected to double in the next thirty years. In general, the African population does not have adequate access to water. Local governments and agencies have been working to improve access to water, and progress has been made. At the current rate of work, the Millenium Development Goal of halving the proportion of people without access to water by 2015 will be not met in 2040 (Stampini et al., 2009). The rate of work cannot keep up with population growth and urbanization.

Groundwater is increasingly developed as an economically viable solution to meet demand for water resources. In Uganda, for example, 70% of water supplied to 782 small towns is groundwater piped via deep boreholes (Mileham et al., 2009). Reasons for developing groundwater include: ease of developing hand-pumps in remote locales; availability during drought; superior chemical and biological quality (compared with surface water sources); and relative low price compared with methods of treating surface water (Dapaah-Siakwan and Gyau-Boakye, 2000; Gyau-Boakye, 2001). In the latter case, for instance, costs of treating water derived from surface sources is approximately twice that of groundwater for communities of less than 5,000 people (Gyau-Boakye, 2001).

Surface water sources are also being developed via small dams and impoundments, but may become less reliable. Per capita surface water supplies in Mali, for instance, are projected to decline by 52% due to an increase of population and a predicted decrease in rainfall. It is anticipated that the per capita decrease in freshwater sources will intensify stress on groundwater resources. If downward climate projections reported for precipitation and surface water availability continue, there may be negative implications for long-term supply of groundwater resources.

2.2 Agriculture

Climate change and resultant alterations to hydrologic conditions affects agriculture via food security. The 75 to 250 million people in sub-saharan Africa could be exposed to increased water stress due to climate change and rain-fed agriculture could be reduced by 50% (Edmunds, 2009). Agricultural production may be severely compromised due to increases in temperature, evaporative demand, and rainfall. Unreliable and declining rainfall already threatens smallholder, subsistence family farms, which form the backbone of most local economies. These small farms are estimated to account for 70% of agricultural production.

To have more reliable, and potentially increased, crop yields for self-sufficiency or export, "efforts should be intensified to support water resource and small-scale irrigation development" (Perret, 2006). Mechanized systems, already in place at some boreholes that access groundwater, can be optimized to extract groundwater for agriculture at much higher rates than for domestic use alone. In Ghana, for instance, there a nationwide drive towards extracting groundwater resources for irrigation of vegetables throughout the year, since over 50% of the country's gross domestic product comes from the agricultural sector, which is primarily rain-fed (Banoeng-Yakubo et al., 2009).

Use of surface and groundwater for agriculture has had varying results. In the US, for example, irrigation for agriculture has led to no issues of food security, but over-extraction of groundwater resulting in groundwater declines, land subsidence, drying up of ecosystems, sea water intrusion, and degradation of groundwater quality (Kinzelbach et al., 2003). In perspective: at the global scale, the largest user of water is irrigated agriculture. Worldwide, the agricultural sector accounts for 70% of water extraction, while less than 5% of African land is currently being irrigated (Taylor et al., 2009). In order to mitigate the effects of climate and combat food security, the African agricultural sector may shift from 5% to 70% of land being irrigated by extracted water.

2.3 Development

Climate change and resultant alterations to hydrologic conditions affects development on multiple socio-economic levels. Achieving the social and economic interest of the population includes providing each community member with opportunities to access water for human health and to experience economic development via agriculture and/or industry. The need for improved access for human health cannot be disputed. On a daily basis, diseases related to poor water or lack of sufficient water kill an estimated 14,000 to 30,000 people in developing nations, of which many are children (Gleick, 2000). Beyond human health, inadequate access to water impacts educational outcomes, and productivity. Absence from school and work due to water-related illness contributes to substandard school performance and productivity, respectively (UNDP, 2006, UNICEF, 2006). Lack of access to water essentially keeps developing nations from developing.

The minimum amount of safe water suggested for improved human health is 50 liters per capita per day (lpcpd), which includes use of safe water for washing, bathing, food preparation, etc (Gleick, 1996). Surveys of water use in rural areas, however, reveal that domestic use accounts for 55% of the total volume extracted, while the remainder is for livestock and gardening (Gleitsmann et al., 2007). The total per capita amount, then, in rural areas is approximately 90 lpcpd (50 lpcpd domestic and 40 lpcpd livestock and gardening).

Rural areas reflect only a portion of the population, as the doubling of population is not evenly distributed. Urbanization is a rapidly increasing trend and urban population is expected to triple between 2000 and 2050. In Mali, for instance, population growth is proportionate to the size of communities: 3.6% for those with more than 5,000 inhabitants, 1.3% for those with 2,000 to 4,999 inhabitants, and 0.6% for those with less than 2,000 inhabitants (N'Djim and Doumbia, 1998). Urbanization increases domestic consumption due to availability of water from a growing pipe network; water use in an urban house (with garden) can be up to 400 lpcpd.

Compounded with urbanization, the demand for water is intensified by mechanized groundwater development. In Uganda, for example, mechanization of groundwater wells expanded dramatically since 2003 (Mileham et al., 2009). These mechanized wells are extracting water for urban areas or a combination of several rural communities. Additionally, these wells may be used for irrigated agriculture, as already discussed.

Finally, development of industry increases demand for water. In the US, for instance, water extraction was 700 cubic meters per person per year at the turn of the century, increasing to 2,300 by the early 1980s, and a subsequent drop to 10% below peak despite continued increases in development (wealth) and population (Gleick, 2000).

For a water supply to provide these socio-economic benefits of development, it must yield sufficient volume to meet all domestic needs, be deemed safe for human consumption, reliable all throughout the year, reasonable distance to fetch water, and maintained by the community. It must also provide sufficient volume for development via agriculture or industry.

3. Climate hange

3.1 Observed and projected

Observed global mean temperatures have been increasing during the last hundred years, with the rate of warming accelerating more recently (IPCC, 2007). There is decreasing frequency of cold days, cold nights, and frost events and concurrent increasing frequency of hot days, hot nights, and heat waves, especially in the latter half of the past century. The increase of temperature observed across the globe is also observed across Africa, with the rate of warming also accelerating during the latter half of the last century. During the last century, Africa warmed by 0.7°C while rainfalls have increased 5 to 10% (IPCC, 2001, 2007). On a sub-continental scale, there are regional variations of temperature trends. For instance, warming is observed in southern and western Africa, and the tropical forests, while cooling is observed near lakes or coastal areas (Boko et al., 2007).

Projections for changes of temperature across Africa vary by scenario. In general, projected increases for temperature are between 3 and 4 °C by the end of this century as compared with the end of the last century (Carter and Parker., 2009; Boko et al., 2007). Warming for Africa is projected to be to be 1.5 times the global mean (Christensen et al., 2007) and, as with observed trends, regional and temporal variations are expected. In general, projections predict up to 40% reduction of rainfall in arid and semi-arid areas but a marginal increase in tropical and equatorial areas (Boko et al., 2007; IPCC, 2007).

Increases of temperature and precipitation are likely to have resultant effects on climate and hydrology, but the ability to accurately predict the impact of temperature increases is currently limited. In the absence of precipitation changes, warmer temperatures alone would likely lead to less streamflow, mainly due to higher evaporation. Considering precipitation also, warming increases the water-holding capacity of the atmosphere and may increase the frequency of very heavy rainfall events, especially in the tropics (Allen and Ingram, 2003; Trenberth et al., 2003).

A variety of methods have been used to evaluate the effect of temperature increases on climate and hydrology, resulting in a broad range of projections. Some of these projections include: increase of annual rainfall and subsequent runoff; decrease of annual rainfall and subsequent runoff; increased evaporative demand; higher evapotranspiration combined with shorter rainfall seasons resulting in persistent soil moisture defecits; soil moisture defecits leading to reduced recharge to groundwater; increase of intense rainfall events; increase of evapotranspiration may negate some of the effects of increased rainfall; increase of arid and semi-arid lands by up to 8%; increases and decreases to recharge of groundwater, varying regionally by up to 53% (Challinor et al., 2007; Olago et al., 2009; Christensen et al., 2007; Milly, 2005; Milham et al., 2009). A regional example is increase of recharge for Sahel and decrease of groundwater recharge to south-west Africa (Kundzewicz and Döll, 2009). On a more ominous note, the warming of the Indian Ocean is projected to disrupt rainfall in eastern and southern Africa, resulting in an additional 50% increase in undernourished people by 2030 (Funk et al., 2008).

With respect to the increase of rainfall intensity and evapotranspiration, evidence suggests that extreme events, such as floods and droughts, are occurring with increasing frequency and duration (IPCC 2007; Peduzzi, 2005). Although extreme weather events often recall images of landscapes desiccated by drought or inundated by flood waters, the reality of extreme event occurrence can be less dramatic. While dramatic types of events are relatively easy to identify in the hydrologic record, other events occur over a wider range of timescales and are not as obvious. Extreme events include high and low precipitation intensity, duration, frequency, or spatial extent; high and low temperature intensity, duration, and frequency; or high and low discharge intensity or duration (Tebaldi et al. 2006). Projected increases in intensities will exacerbate drought and flood events both of which threaten crops yield and food security (Challinor et al., 2007).

3.2 Alterations to surface water and groundwater

Extended departures of streamflow, temperature, and precipitation from historic mean annual values will affect availability, and quantity of water. Volumes of water resources developed as surface water and groundwater are often estimated, since surface waters are not always adequately monitored and hydrographic networks are shrinking, while groundwater networks are scarcest of all (Kundzewicz and Döll, 2009).

Surface water and groundwater sources are both dependent on precipitation. Rainfall variability is high, with multi-year events of higher and lower than average rainfall. In some instances, inter-annual variability is such that 95% of annual rainfall totals deviate between 16 and 45% from the mean (Cater and Parker, 2009). Large trends of decreasing rainfall were widespread in the Sahel from the late 1950s to the late 1980s with some recovery through 2003 (Nicholson, 2005; Dai et al., 2004), and to-date it is not clear if drought conditions have ended. Inter-annual variability of rainfall is linked with inter-annual variability of surface water (runoff) such that wetter periods observe greater volumes of stream flow surface water and drier periods observe reduced volumes of surface waters. Relationships between reduced rainfall and declining stream flows have been observed for streams in the Central Kenyan Rift, Volta River Basin, and Niger River Basin (Olago et al., 2009; Mahe 2009).

Relationships have also between observed between reduced rainfall, declining stream flows, reduction of recharge to groundwater, and subsequent decline of groundwater levels. The relationship between rainfall and recharge is not necessarily linear, with the possibility of recharge occurring sporadically on regional and temporal scales. In the Ethiopian highlands, for instance, recharge from monsoonal rains is released by spring and seeps in the dry season but this monsoonal recharge does not necessarily contribute to inter-annual groundwater storage (Walraevens et al., 2009).

Contributing to the non-linearity of the relationship between rainfall and recharge, some studies suggest that a certain threshold of rainfall (annual or event-driven) must be reached before any recharge to groundwater occurs. The large inter-annual variability of rainfall, thus, may lead to large inter-annual variability of recharge (Eilers et al., 2007; Edmunds, 2009; Olago et al., 2009). Insignificant recharge is thought to occur when rainfall is generally less than 200 mm yr^{-1}, though some recharge during individual intense events less than that amount (Scanlon, et al., 2006; Edmunds 2009). One study observed recharge taking place approximately every 10 years for a duration of a 3-year pluvial event (Olago et al., 2009). Individual intense events, in general, may be contributing more to recharge than the sum of all daily rainfall events (Taylor and Howard, 1996; Eilers et al., 2007; Owor et al., 2009).

The decline of groundwater levels has been observed during periods of sustained annual reduction of rainfall such as during drought. Complete dewatering of certain aquifers was observed in Ethiopia during drought (Walraevens et al., 2009) and decline of groundwater levels observed during drought in Burkina Faso (Thiery et al, 1993) and in the upper Niger Basins (Bamba et al., 1996). It is suggested that the volume of groundwater extracted should not be greater than the volume recharged (Kinzelbach et al., 2003), and probably much less.

In arid to semi-arid regions, Saharan regions, significant recharge events occurred about 5,000 years ago (Edmunds et al., 2004), so it must be recognized that substantial recharge has likely not occurred recently and that groundwater resources are essentially non-renewable (Edmunds 2009).

4. Caveats

There is inherent uncertainty in the GCMs for projections across the globe. There is "substantial" uncertainty in the projections and resultant climate and hydrologic effects for Africa (Taylor et al., 2009). Perhaps some of the greatest uncertainty is for the latter part of this century for the West African Sahel, as some projections predict larger rainfall while others predict longer, intensified drought (Lebel et al., 2009). Uncertainty is, in part, due to varying time frames, assumed socio-economic standards, difficulties linking hydrologic models to GCMs, land-use changes, and the lack of understanding of the climate-water relationship.

Uncertainty may also be attributed to the shortage of available historical and current observational data. A study linking climate and hydrology in Uganda evaluated trends in temperature and discharge, but could not determine trends in precipitation with the caveat that only one precipitation station was available for study area (Nyenje and Batelaan, 2009). In general, there is a paucity of available climate and hydrologic data for the Africa continent, even though these are of great importance for sustainable water resources management (Baisch, 2009). Demand for water during droughts of the 1970s and 1980s, placed emphasis on rapid development of water sources. As a result, studies of groundwater, surface water, and rainfall were often not prioritized and balance of the local water resources is not well understood. Recently, there has been more effort to study and characterize aquifer parameters, extraction rates, seasonal groundwater level fluctuations, rainfall, and relationships between groundwater and surface water, but it will take time to close the knowledge gap.

Computational technology has allowed for models of surface water and groundwater to be used in scientific research with output potentially used for decision making by policy-makers. These models are useful for forecasting the potential impacts of climate change projections and especially useful for testing and evaluating alternative resource management strategies. Models range from simple spreadsheets to complex codes and, depending on complexity, computing capacity makes it possible to run many models on a desktop system. As a case study, a spreadsheet multicriterion decision analysis model was used to analyze sensitivity of stages of drought on the Niger River and impacts to priorities of decision-makers (Traore and Fontane, 2007). Results have been attained from simple models to analyze natural groundwater level variation (Thiery et al., 1993), lumped models to estimate evapotranspiration (Ardoin et al., 2001), water balance approaches to evaluate water resources (Asomaning, 1992), and water balance approaches via groundwater models such as MODFLOW (Lutz et al., 2007; 2009; 2011).

Most recently, remotely-sensed data have been used to fill in gaps of the historical and current observational data. Satellite data from the Gravity Recovery and Climate Experiment (GRACE) has been used to develop estimates of freshwater storage for a water balances in the Congo (Crowley et al., 2006) though technical challenges remain for using the GRACE data (Taylor et al., 2009). Evaporation is an extremely difficult parameter to measure, requiring expensive field equipment that. Remotely-sensed data and has been used to estimate evapotranspiration in the Volta Basin of Ghana (Compaoré et al., 2008), and to estimate streamflow, lake, and marsh height in the Lake Chad Basin (Coe and Birkett 2004).

5. Path forward

The combination of demand for access to water from development, irrigation for agriculture, and growing population are already challenging for developing nations. And, compounded with mitigating the potential effects of climate change projections, there is growing growing concern over the availability of water resources (Ndjim and Doumba, 1998; Taylor et al., 2009).

The caveat of data availability and implications for modeling has already been discussed. A further caveat is data availability and implications for complex feedback loops between natural resources, land use, hydrologic and climate cycles, policy, population growth, agriculture, socio-economics of development, and stakeholders. Inadequate understanding of water resources, failure of scientific community to research and convey new discoveries, and a lack of societal and political awareness to act on available scientific evidence (Edmunds 2009) causes difficulties for developing policies to guide water resources development. Information needed to asses water resource sustainability is not readily available, non-existent, or are not collected (Gleick, 1998). And, especially at the local scale, agencies often operate under constraints of limited expertise, funding, resources, and data.

Development of water resources, in particular groundwater, has historically been approached from a perspective that supply can be plentiful. And while hand-pumps do extract very little water with respect to the larger water balance (Lutz, 2007, 2009, 2011), increased water availability to Africa populations during the past few decades has already resulted in localized draw-downs of water tables and loss/damage to ecosystems (Edmunds 2009). Regional failure of an aquifer is unlikely, though increased demand may cause localized failure at a particular source of water. Unfortunately, few data exist upon which to base extraction policies (MacDonald et al., 2009).

Declines of groundwater due to drought, rather than abstraction, have been observed in the Khalahari Karoo/Stampriest Artesian Aquifer and Lake Chad Basin Aquifer System (Scheumann and Alker, 2009). Cooperative commissions have been formed on transboundary aquifers, but they are less developed than the commissions formed for transboundary rivers and lakes, such as the Lake Chad Basin Commission, and Orange-Senqu River Basin Commission (Scheumann and Alker, 2009).

Promotion of linkages among stakeholders is essential. Water planning and decision making is often left to a narrow range of people who do not necessarily include rural interests, minority groups, environmental groups, and academics, for instance (Gleick, 1998). Bureaucrats at the national ministerial level often have little or no knowledge on the impact of a program on the intended beneficiaries, suggesting that any attempt to assess the impacts of rural water supply programs in the developing world should solicit information from regional and district representatives (Akuoko-Asibey, 1997).

6. Conclusion

The assumption of a relatively constant climate has been increasingly called into question with the recognition that climate variability is greater than commonly perceived, and may increasingly impact water resources. Furthermore, evidence suggests that extreme events, such as floods and droughts, are occurring with increasing frequency and duration. Stationarity of climate and hydrology should no longer be assumed for water resources planning. There is a growing need to consider susceptibility to, and planning for, more extended departures of streamflow, temperature, and precipitation from historic mean annual values.

The discussion of complex feedback loops between natural resources, land use, hydrologic and climate cycles, policy, population growth, agriculture, socio-economics of development, and stakeholders circles back to the impacts of climate change. Much effort is going on to close major gaps existing in the knowledge of climate and hydrology in Africa. The HAPEX-Sahel study Journal of Hydrology, the ongoing African Monsoon Multidisciplinary Analysis (AMMA) investigating tropical monsoon dynamics over West Africa, in particular the AMMA-Catch observing system monitoring land use/land cover and hydrology at sites in Benin, Niger, and Mali, and NCAR cloud seeding over Manatali Dam in Mali. These are just a few examples.

There is need for impact assessments at local scales and simple, but accurate tools and techniques to assess impacts to water resources is essential to mitigate climate change. Increased demand resulting from increase of population, potential for irrigation to agriculture, and development. Some of the greatest challenges that developing nations continue to face include providing access to water, while successfully developing and managing it as an environmental resource, and mitigating the potential effects of climate change as this resource continues to be developed.

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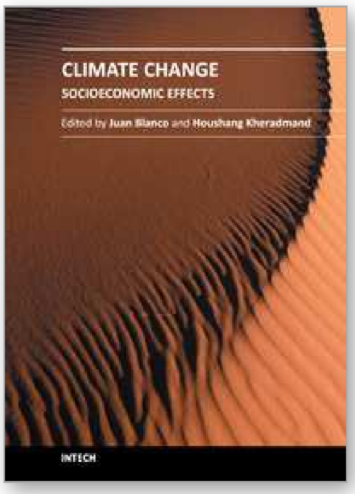

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This book shows some of the socio-economic impacts of climate change according to different estimates of the current or estimated global warming. A series of scientific and experimental research projects explore the impacts of climate change and browse the techniques to evaluate the related impacts. These 23 chapters provide a good overview of the different changes impacts that already have been detected in several regions of the world. They are part of an introduction to the researches being done around the globe in connection with this topic. However, climate change is not just an academic issue important only to scientists and environmentalists; it also has direct implications on various ecosystems and technologies.

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