Water Resources Management in Tanzania: Identifying Research Gaps and Needs and Recommendations for a Research Agenda

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Abstract
This paper aims at identifying research gaps and needs and recommendations for a research agenda on water resources management in Tanzania. We reviewed published literature on water resources management in Tanzania in order to highlight what is currently known, and to identify knowledge gaps, and suggest areas that need further research. The paper is in four parts which address: water resources as impacted by climate change; management of water resources in Rainfed agriculture; management of water resources in irrigated agriculture and water management catchment studies. Review of water resources management in Tanzania; Global literature review on water resources management; Knowledge gaps on water resources management in Tanzania; and Proposed research agenda and researchable issues. Therefore, the main objective of this paper is to review published literature on water resources management in Tanzania in order to highlight what is currently known, and to identify knowledge gaps, and suggest areas that need further research. However, the scope of the paper is limited to the following core areas: water resources as impacted by climate change; management of water resources in Rainfed agriculture; management of water resources in irrigated agriculture and water management catchment studies.

Keywords: Water resources management, Research gaps, Research agenda, Climate change, Land use change.

Introduction

The Tanzanian economy is highly dependent on water resources. Nearly half of Tanzania's GDP comes from the agriculture and livestock sectors (Salami *et al.,* 2010), which are highly dependent on water resources. However, these water resources are currently vulnerable to climate change and variability. In recent years, the major hydro-plants in the country underperformed due to low river flows. The power shortages caused significant economic losses in many sectors such as industry, agriculture, and mining, to mention only a few (Mwakalila, 2007). Water is, therefore, a key resource that requires good management.

The social and economic circumstances prevailing today have made particular demands upon the country's water resource base and the environment, and its sustainability is threatened by human-induced activities. Over the past 20 years, these demands have intensified with the increase in population and concurrent growth of economic activities requiring more water. These demands include hydropower generation, irrigated agriculture, livestock keeping, domestic use, and wildlife use (URT, 2002).

Water scarcity is experienced in many places and sectors in Tanzania due to unreliable rainfall, the multiplicity of competing uses, and the degradation of sources and catchments (URT, 2002; Munishi *et al.,* 2008). There are also increasing challenges in managing the multiple trans-regional watercourses, and in strengthening water resources management policy, and the legal and institutional frameworks. Inadequate regulations to monitor groundwater resources development has led to underutilization of the resources, and in some places, overexploitation and interference in the existing water sources. Fragmented planning, implemented following sector, regional or district interests, aggravates this situation even further (URT, 2002).

Water resources management, especially in agriculture, is a critical factor in the reduction of poverty and hunger in Tanzania. This is possible due to the fact that the available technological capability for addressing water management problems is huge. Various researches related to water resources management have been carried out in the country. At the same time, the exploitation of its potential is constrained by our inability to apply it within the realities of political and social systems. Scientific and technical understanding should be united with the goals of society. Optimal technical approaches may be socially unacceptable, and compromises often have to be reached. Water resources management research goals must be based on a blending of technical options with the public's view of what it deems to be an acceptable solution to the problem at hand. Technicians must take steps to ensure that the public view is understood and incorporated in their designs. While technology is only one of many factors affecting water resources decision making, it is ubiquitous in that it permeates the planning, policy-making, regulatory, design, and implementation processes.

For many years, Tanzania has been struggling to achieve food self-sufficiency. In order to achieve this, many programs and strategies have been formulated and implemented. These include ASDP (2001), MKUKUTA (2005), KILIMO KWANZA (2009), and very recently SACGOT (May, 2010), to mention a few. In all these programs and strategies, water, and specifically agricultural water, plays a central role. Some of the past research focused on breeding crops that can cope with droughts given the fact that two-thirds of the country is semi-arid and crop production is mainly rainfed (Hall, 2004; Xoconostle-Cazares *et al.,* 2011). With the emerging new challenges, for example, due to climate change (Yanda and Munishi, 2007; Arndt *et al.,* 2011), research will be required in order to have sustainable agricultural production for the reduction of poverty and hunger in Tanzania.

Water management affects related lands, and land use practices affect related waters. The linkages between land–water management practices underscore the need to coordinate water resources planning and management with land use planning and regulation. It is for this reason that this thematic area, 'Water Resources Management', will include researches that link both the water–land interface with a major focus on agricultural water management and the new challenges toward achievement of the Feed the Future (FtF) program by increasing agricultural productivity, which is guided by sound research results and guidelines.

Therefore, the main objective of this paper is to review published literature on water resources management in Tanzania in order to highlight what is currently known, and to identify knowledge gaps, and suggest areas that need further research. However, the scope of the paper is limited to the following core areas: water resources as impacted by climate change; management of water resources in Rainfed agriculture; ; management of water resources in irrigated agriculture and water management catchment studies.

Review of water resources management in tanzania

Climate Change Impacts on Water Resources in Tanzania

The effects of climate change and variability such as rising temperature and changes in rainfall are undeniably clear, with impacts already affecting ecosystems, biodiversity, and people (Vera *et al.,* 2010). Africa is among the most vulnerable regions in terms of the impacts of climate variability and change (Intergovernmental Panel on Climate Change (IPCC), 2007; Fischer *et al.,* 2005). The high vulnerability of Africa to the impacts of climate variability and change is also attributed to its low adaptive capacity (UNFCCC, 2006). The projected climate change will have far-reaching, negative impacts on the availability of water resources, food and agricultural security, human health, tourism, coastal development, and biodiversity (Mugabe *et al.,* 2010). The impacts have potential to undermine, and even undo the progress made in improving the socio-economic well-being of Tanzanians.

Climate change is projected to have both positive and negative consequences for Tanzania's water resources (URT, 2003; OECD, 2003; World Wide Fund For Nature (WWF), 2006;). According to the URT (2003), in Tanzania high temperatures and less rainfall during already dry months in the river catchments are projected to affect the annual flow to the River Pangani by reductions of 6-9% and to the River Ruvu by 10% due of climate change. According to the URT (2003), the Rufiji River, which houses the Mtera and Kidatu hydropower stations, is expected to experience an increase in river flow of 5–11%. According to Wambura (2014) precipitation signal shows that stream flow is projected to increase for the near term climatology (2010 – 2039). However, WWF (2006) warned that, it may also be likely that the increased precipitation will come in a few very large rainstorms mostly during the already wet season thereby adding to erosion and water management issues and complicating water management.

Nevertheless, decreases in runoff could potentially have serious effects on socio-economic activities in the regions of Dar-es-Salaam, Morogoro, Tanga, the Coast, and Kilimanjaro. Recently, civil conflicts have been taking place between livestock keepers and farmers over pasture and water, for example in the Morogoro region. The cost of realizing the UN Millennium Development Goals is likely to rise, as poor access to water impacts adversely on livelihoods, health, and productivity (CARE, 2006).

Other studies undertaken to project the impacts of climate change on water resources in Tanzania include Mwandosya *et al.* (1998) and de Wit and Stankiewicz (2006). Most of these studies used GCMs in their analysis and concluded that some areas of the country, such as the Pangani basin area, may receive more rainfall under various climate change scenarios, while the central regions might receive less. In terms of temperature increases, the two studies reported a range of 1.5°C–2°C for the first half of this century and around 2°C–4°C for the second half. These findings are also within the range predicted for East Africa (IPCC, 2007). It is worth pointing out that, in assessing the predictions of these studies, other drivers of climate change and water resources have roles. These include factors such as land use change, population growth, and the rate of urbanization. These factors need to be considered and incorporated; otherwise planning of adaptation strategies will remain difficult and incomplete.

Rainfed Agriculture and Water Resources Management in Tanzania

Many people in the world rely on Rainfed agriculture, which is highly vulnerable to changes in climate variability, seasonal shifts, and precipitation patterns. In Tanzania, agriculture is the foundation of the Tanzanian economy since it accounts for about half of the national income, three-quarters of merchandise exports, and is the source of food, providing employment opportunities for about 80% of Tanzanians (Salami *et al.,* 2010). About 70% of Tanzania's crop area is rainfed. Food crop production dominates the agriculture economy as it accounts for about 65% of agricultural GDP, with cash crops accounting for only about 10%, and about a quarter of the remainder accounted for by the livestock sub-sector (URT, 2014). The major constraints facing the agriculture sector are a reduced labour force, decreasing land productivity due to the application of poor technology, and the dependence on unreliable and irregular weather conditions. Both crops and livestock are adversely affected by periodical droughts.

The effects of the climate variability have contributed to the shortage of food and to an increase in the rate of malnutrition in the children in the country. The ministry of health under the National adaptation programme of action (NAPA). (URT, 2007; Shemsanga *et al.,* 2010) already show alarming figures following the continuing failure in agricultural productivity in Tanzania. Being a staple food for most Tanzanians, maize that is widely grown in Tanzania is projected to be affected the most by recent climate variability. Mwandosya *et al.* (1998) had projected that if the greenhouse gas CO2 doubles and the average temperature increases by between 20C to 40C, then the maize harvest will decrease by up to 33%. The situation will even be dire in some regions such as Dodoma and Tabora, where up to 80% of this important source of carbohydrate is predicted to be lost.

The alternative to the effects of drought in Tanzania's agricultural sector would involve strengthening irrigation projects. However, water for irrigation is becoming very unreliable and, thus, places where major economic activities depend on irrigated agriculture will have severe economic hardship because of the continuing climate variability (URT, 2003).

Even worse is that in places where climate change is predicted to increase rainfall, flooding of coastal regions with further effects on agriculture is imminent. Flooding is associated with nutrient leaching, water logging, and the sweeping away of crops and the fertile topsoil. These effects have already been reported in many places in those regions (URT, 2003). In addition, infrastructure such as roads is also swept away by floods, which complicates the transportation of agricultural produce and farm inputs to market places and farming areas, respectively; hence, leading to poverty intensification.

Studies in Rainfed agriculture addressing some water management issues include those targeted at improving the availability of water for plant growth in the semi-arid areas (SWMRG, 2001). According to the SWMRG (2001), It is estimated that in many farming systems, more than 70% of the rain falling directly on a crop-field is lost as non-productive evaporation or flows into sinks before it can be used by plants. In extreme cases, only 4–9% of rainwater is used for crop transpiration. Therefore, in rainfed agriculture, wastage of rainwater is a more common cause of low yields or complete crop failure than absolute shortage of cumulative seasonal rainfall.

Another study carried out by the SWMRG (2005) in the semi-arid areas of Tanzania aimed to develop and promote strategies that could improve the livelihoods of the poor living in semi-arid areas. They reported that current institutional and regulatory mechanisms limited access to common pool resources (CPR) such as water and land by the poor. It was also observed that a gap exists between the emphasis given in national policies, strategies, and programs, and what is actually practiced by farmers in semi-arid areas. There is, therefore, a real problem in Tanzania, whereby national-level strategies and policies are not taken into account at the local level. They include the formation of an autonomous committee for land management in villages, with sub-committees for residential land, agricultural land, and grazing land, the preparation of land use plans to demarcate grazing and agricultural land, and that water allocation should consider spatial and seasonal aspects (SWMRG, 2005).

Improving Productivity of Water under Rainfed Agriculture Systems

Given the persistently growing pressure on freshwater and soil resources, it follows that the challenge of feeding the ever-increasing world population is, to a large extent, about improved water productivity within present land use. Producing more crops, livestock, fish, and forest products per unit of agricultural water use holds a key to both food and environmental security. A variety of options exists for improving the productivity of water in agriculture through breeding, better management practices, and supporting policies and institutions. As water productivity can be quantified, it enables improvements to be charted, thereby encouraging faster progress. Therefore, the main reason for improving agricultural water productivity (water productivity in crop, livestock, and aquaculture production) is to meet rising demands for food from a growing, wealthier, and increasingly urbanized population, while there are pressures to reallocate water from agriculture to cities, and to make more water available for environmental uses. An additional reason derives from the link between poverty reduction and economic growth. For the rural poor, a more productive use of water can mean better nutrition for families, more income, and productive employment.

In Tanzania, studies directly aimed at increasing water productivity under rainfed agriculture systems are scarce. However, the total benefits and the amount of water depleted are rarely known, monitored, or measured. Often, only the amount of the target crop is considered as the benefit obtained. Water recycling is always neglected. It is for this reason that productivity figures quoted in Tanzania are so low. For example, in Tanzania, productivity of water of 0.1–0.14 kg/m^3 for rice and 0.22–0.32 kg/m^3 for other cereals have been recorded, which are even much lower when compared to the global water productivity situation.

Results from the study carried out by Mahoo *et al.* (2007) in the Rufiji River basin to assess the productivity of water showed that the concept of productivity of water is not well understood by many stakeholders and the practice of assessing productivity is insufficient. A more comprehensive analysis of water use and productivity in the Great Ruaha basin was carried out by the RIPARWIN (Raising Irrigation Productivity and Releasing Water for Intersectoral Needs) project (Kadigi and Mdoe, 2004). This study on livelihoods and the economic benefits of water utilization showed the highest values of water for livestock, brick making, and domestic uses, averaging at around a dollar per cubic meter (m^3) of water consumed. Understanding such a value for water is very important among stakeholders for efficient allocation of basin water resources.

Some disagreements on actual water allocation will still remain due to the differences in values, goals, priorities, and aspirations of people. However, a common understanding on the value of water and productivity is a prerequisite in ensuring the equitable sharing of basin water resources. Unfortunately, there is evidence of a problem of a lack of common understanding and practice of the concepts of productivity of water among stakeholders in Tanzania. As a result, it is a common practice to evaluate irrigation schemes in terms of yield, while it may have been more logical to measure performance per unit of water use (i.e., kg/l/s/ha).

Water Resources Management in Irrigated Agriculture Systems in Tanzania

Under the Smallholder Irrigation Improvement (SII) scheme of the RBMSIIP, on the other hand, in terms of irrigation efficiency, the average baseline values of irrigation efficiency for the traditional irrigation schemes improved by about 67%. This was derived from an average of 86% for conveyance efficiency, 76% for field canal efficiency, and 47% for application efficiency (MAFSC, 2006). All these have a noticeable impact on the management of irrigation schemes, of basin water availability, part of which serves to satisfy in-stream environmental flow requirements. Further increases in irrigation efficiency can be achieved if intensive on-scheme training of irrigators' groups in water management and operation and maintenance (O&M) is maintained.

Similarly, crop yields were reported to have increased. Rice yields and total production almost doubled in both the Pangani and Rufiji basins from 2.0 tons/ha and 1.8 tons/ha for the Pangani and Rufiji basins, respectively, before the project, to an average of 5.0 t/ha. The yields have been reported to be up to 8.0t/ha in some cases. Production of other crops such as onions, tomatoes, cabbages, and other vegetables, generally grown during the dry season, also increased significantly. The bean yield increased from 0.4t/ha to 1.5 t/ha.

Water Resources Management and Environmental Flows in Tanzania

An environmental flow is a flow in a river or into a wetland or coastal zone (which may include groundwater) that maintains the ecosystem in a desired ecological condition, which maintains goods and services for people, and supports biodiversity. This condition is decided on by society and is a compromise between economic, social, and ecological values of water for various uses. Environmental flow assessment thus provides a key element in integrated water resources management.

Environmental flow assessments have been carried out in a number of basins in Tanzania such as the Pangani, Wami-Ruvu, Rufiji (all in Tanzania), and Mara (Dickens, 2010) basins. In the Pangani River basin, Dickens (2010) reported that implementation of environmental flows was awaiting the conclusion of the project. Among the limitations and gaps that Dickens (2010) reported were a lack of information on ecological importance; resources quality not being described; insufficient local involvement; not all sections of the project were well focused on environmental flows; and stakeholder involvement was inadequate. Similar results were reported by Gowing (2004) in a comparative study carried out in the Mkoji sub-catchment in the Great Ruaha River. The results from the study by Gowing (2004) indicated that an integrated approach to land and water management that requires assessment of environmental services that are related to land use and stream flow was lacking in the Mkoji sub-catchment. In addition, the study revealed that there was limited knowledge on the baseline condition represented by the 'natural' condition of the river basin and the concept of water for 'human reserves' should be extended beyond a narrow application to stream flow and/or groundwater.

In another study carried out by the WWF Tanzania Country Office (WWF-TCO, 2010) on environmental flow assessment in the Great Ruaha River, they reported that one of the preferred options for the restoration of flows in the Great Ruaha River included institutional strengthening and support to ensure improved water resources management. The key recommendations from the study include the need for a socio-economic survey as well as an up-to-date study to disaggregate anthropogenic impact from climate-change impact. Additionally, the study emphasized the need to increase the number of rating measurements at gauging stations, spot measurements taken at catchment outlets, and an increased number of observation stations (discharge, rainfall, climate, groundwater) around the Eastern wetland, and to carry out further field-measurement studies to accurately estimate groundwater flows and evapotranspiration from the wetlands. Harmonization of data sets, and further bathymetric surveys were also indicated as being important. Further sampling of fish and invertebrates at a range of flows was recommended, together with monitoring of riparian vegetation. The need for more recent water quality data was also highlighted.

The study by Kashaigili *et al.* (2006) on environmental flow modelling in the Usangu wetlands showed that between 1958 and 2004, inflows to the wetland declined by about 70% in the dry season months (July to November) as a consequence of increased human withdrawals, primarily for irrigation. This resulted in a decrease in the dry season area of the wetland by approximately 40% (i.e., from 160 km2 to 93 km^2). In the last decade, outflows from the wetland have ceased for extended periods. An environmental flow model indicated that a minimum dry season outflow of approximately 0.6 $m^3\ s^{-1}$ is essential to sustain the basic ecological condition of the river. To maintain this outflow from the wetland, a minimum average dry season inflow of approximately 7 m3 s^{-1} (i.e., approximately double the current dry season flows) is required. To achieve this, dry season flows in the perennial rivers discharging into the wetland would have to be apportioned so that 20% is used for anthropogenic purposes and the remaining 80% discharges into the wetland.

There is significant potential for improving water use efficiency. However, to ensure minimum downstream flow requirements, consideration should also be given to active water management within the wetland itself. It is for this reason that sustainable water resources management in the Great Ruaha River basin is of national importance in terms of utilization of its water resources for significant crop production, maintaining a RAMSAR wetland site, meeting the ecological needs of the Ruaha National Park, and the generation of hydro-electric power. However, one of the biggest challenges is how to balance and meet the different water needs of the different sectors without detrimental effects. The question of environmental flows is an issue that is not well understood and is sometimes neglected. There is a need to look into this and come up with criteria and guidelines to make sure that environmental flow is maintained in all the river basins in the country.

Water Resources Management and Catchments Environment in Tanzania

In view of the current challenges in water resources management in Tanzania, integrated water resources management is needed to ensure that water does not become a constraint to national development. This call for a new vision: "A country where there is equitable and sustainable use and management of water resources for socio-economic development, and for maintenance of the environment" (URT, 2002). The existing approach to water resources development is sector oriented and does not fully recognize the multi-sectoral linkages in planning the use of water resources. Furthermore, it is based on regional development and does not focus on the institutional capacity to manage water resources. It is also oriented more toward the development of the water resources, and not on the protection, or management of the water resources, and is based on regulation as a primary instrument for implementing the water policy. An integrated approach addresses participatory, multi-sectoral, multidisciplinary river basin management, which recognizes that water, is a scarce resource, and which integrates the linkage between land use and water use, and recognizes the important role water ecosystems play in the national economy.

Evidence from studies carried out by Dungumaro (2006) indicate that for quite some time water resources management in the country has been carried out in isolation from other resources such as land, and the focus has been on a single purpose for water use. Under the single-purpose approach, Dungumaro (2006) reported widespread degradation of water resources and water scarcity in the study catchment area. In order to achieve the benefits of IWRM, issues pertaining to population increase, environmental, socio-economic, and political factors (also referred to as 'determinants') must be addressed. The National Water Policy (URT, 2002) recognizes that the river basin or sub-basin shall be the planning unit, and planning shall involve all stakeholders, shall be intersectoral in character, and finally, that it shall consider requirements for biodiversity and human health. This is often said rather than done. It is for this reason that a review of catchment studies is necessary, because water resources in terms of quantity and quality have a strong bearing on how catchments are managed and/or utilized.

Catchment studies in Tanzania date back to the 1960s under the East African Agricultural and Forestry Research (EAAFRO), though the focus was more on the effects of deforestation/afforestation on catchment discharge (Edwards, 1979). Although the hydrological effects of complete clearing of forests are adequately established few basic studies have been carried out to assess the effects of deforestation on the various components of the hydrologic cycle in Tanzania. Information relating the effects of deforestation on changes in the hydrologic cycle including water quality changes and crop evapotranspiration is scarce.

In order to quantify the impacts of forest changes (deforestation and afforestation) on river flows, it is important to carry out modelling studies, preferably for small forested catchments, to understand the interactions between the forest cover, surface, and subsurface water. In this case, distributed models are appropriate. However, such models require extensive data sets that can only be assured once additional flow gauges, rainfall and climatic stations, and observation wells are installed. Whilst observation wells, within the study catchments, will provide information regarding the subsurface conditions (e.g. groundwater fluctuations), river flow gauges will provide the resulting surface flow fluctuations, while rainfall and climatic stations will provide information on the background climatic fluctuations. Monitoring of vegetation cover changes can therefore be linked to these hydro-geoclimatic fluctuations once suitable distributed models have been calibrated for selected forested catchments.

Other recent studies include those by Marloes (2009) and Kinoti *et al.* (2010), carried out in an un-gauged Makanya River catchment in the Pangani basin. The study by Marloes (2009) reported that the current hydrological and water resources situation in the catchment is a result of anthropogenic influences. There is increased water usage in the upper parts of the catchment, especially through irrigated agriculture. Given the fact that there are no formal agreements in existence between the highland, midland, and lowland water users, much of the water is used in the upstream part of the catchment. With the base flow no longer reaching Makanya village (i.e., the location of lowland farmers), the farmers were forced to change their irrigation practices from full to spate irrigation. Furthermore, changes in land use in the upstream parts have also impacted the hydrological processes, though due to the lack of historical data, this was not quantified. The downstream farmers partly benefit, as flash floods generated in the highlands reach Makanya, replenishing the unsaturated zone and local groundwater bodies, and depositing fertile sediments. However, due to poor control, the flash floods cause damage to crops.

The study by Kinoti *et al.* (2010) examined understanding the rainfall–runoff relations in the Makanya catchment using modelling approaches. The estimation of rainfall in this study was based on the blending of the geostationary MeteoSat second generation (MSG), infrared channel with the low-Earth orbiting passive tropical rainfall measuring mission (TRMM), and microwave channel satellite data. Comparison of the results obtained from the blended TRMM–MSG with the available ground gauge data for the 2004 and 2005 periods gave a good correlation of about 80%. In conclusion, the developed TRMM–MSG blending procedure was found to be a reliable and robust way of obtaining spatial–temporal rainfall distribution of a given area and particularly so for arid and semi-arid lands (ASALs) such as Makanya, with sparse data-acquisition networks.

In a study carried out by Gomani *et al.* (2010) in Ngerengere River catchment to establish a hydrological monitoring network, integrated participatory approaches were used. The results indicated that the integrated participatory approach helped considerably in setting up and maintaining the monitoring network. Another key result from the study by Gomani *et al.* (2010) is a framework or model that can be used for establishing hydrological monitoring networks in catchments. However, the framework requires further work to test its applicability in other catchments.

A similar study was carried out by Ludovic (2012) in the Morogoro River and Ngerengere River sub-catchments. The study aimed to explore and model the influence of land use change and rainfall variability on water discharge in the two river sub-catchments. An empirical model was developed linking land use change and water discharge. Although the methodological framework used to derive the model can be used in similar catchments, transferability to similar catchments in other basins should be studied and explored. Understanding the areal changes, transformation, dynamics, and their associated trends will shed more light on the relationship between land use changes and water resources in river basins.

As stated earlier in the section, catchment studies in Tanzania are scarce, and the few that have been conducted have been driven by projects, and once the projects come to an end, the monitoring comes to an end. Given the current rate of land use changes that are taking place in the country and the effect this has on water resources, the study has shed some light on these effects on the water resources base.

Ground water resources in Tanzania

In Africa, groundwater is the major source of drinking water and its use for irrigation has been forecasted to increase substantially to combat the growing food insecurity. Despite this, there is little quantitative information on groundwater resources in Africa, and groundwater storage is consequently omitted from assessments of freshwater availability (www.iopscience.iop.org).

In Tanzania, some studies have been undertaken in different parts of the country. Many of these studies were undertaken during projects and/or programs, and sometimes there is a lack of coordination. For example, studies conducted by Ghiglieri *et al.* (2010) in Arumeru district in Arusha, reported that both shallow and deep circulating groundwater is present in the volcanic district surrounding the northern slopes of Mt. Meru. The former occurs in perched aquifers in unconsolidated or semi-unconsolidated sediments and is rather scarce. These aquifers are of limited extent, and are largely restricted to sandy riverbeds and superficial paleo-lake sedimentary deposits. Both intermediate and deep groundwater circulation systems where the permeability of the aquifer, and the elevation difference between the recharge and the discharge areas encourages relatively deep infiltration are present. The deepest infiltration occurs where brittle rock has been fractured or faulted over a wide area. In these cases, a large recharge area, in conjunction with substantial rainfall, can generate productive wells and springs.

Studies carried out in the semi-arid South-Pare Mountains, Tanzania, by Mutiibwa *et al.* (2008) using hydro-chemical mapping, hydrograph separation, and electrical resistivity tomography (ERT), reported that the Makanya catchment was losing significant amounts of groundwater to neighbouring catchments. The Makanya River forms a sub-catchment of the Pangani River basin.

In a study carried out by Fish (2011) in a small, spring-dominated catchment on Mt. Hanang, Tanzania, to determine general aquifer characteristics and hydrologic functioning, he used geochemical analysis, recession flow analysis, and water balance models to characterize the system. The results indicated a geochemistry that is a meteorically-recharged, shallow aquifer system with rapidly circulating groundwater. The recession flow varied from year to year, but an average monthly constant of 0.151/month was calculated for the 2004–2009 discharge dataset. Other studies carried out on the slopes of Mt. Kilimanjaro involved a hydro-chemical and isotopic synoptic sampling program in January 2006 to characterize the hydrogeology, hydrology, and water quality of the area (Mckenzie *et al.,* 2009). The results, including the tritium values, show that the hydro-geologic system is comprised of both local and regional flow systems, and that regional rivers are receiving significant inflow from shallow groundwater, and that at very high elevations the hydrologic system is derived from groundwater, precipitation, and glacial melt water.

On the other hand, the effect of changes in land use and vegetation cover on water yield from the Ruhudji catchment in southern Njombe, Tanzania, and the effect of afforestation on the water yield were studied by Makwetta (1999). Land use vegetation cover was determined from topographic maps produced in 1963 and 1967. More recent aerial photos were also used. Rainfall and runoff patterns were identified, and 3- and 5-year means were used to test any variation. Using correlation techniques, the relationship between rainfall and runoff was tested. The results showed very little correlation between the two variables. The observed limited correlation could be associated with Land use vegetation cover change in the area.

Ground water and climate change in Tanzania

Global warming is altering regional climates in ways that are still to be fully understood. Some regions will experience increases in precipitation, some decreases; some will experience increased cloudiness, some less; and all will experience increases in temperature and sea levels (Thornton *et al.,* 2006). In most regions, there will be an increase in climate extremes, leading to more frequent and more extreme floods and droughts. These changes will impact both surface and groundwater systems in diverse ways. Total quantities of surface runoff and groundwater recharge will be increased or decreased, and the timings and periodicity of these replenishment events will change (Intergovernmental Panel on Climate

Change (IPCC), 2007).

Groundwater is not a universal panacea to water problems and it is subject to degradation. Therefore, careful characterization of the resource is required to guide investments in water supply, and to manage the resource to minimize environmental degradation and widespread depletion. Limited knowledge of African groundwater resources is evident from the paucity of information on groundwater included in the IPCC (2007). Fourth Assessment Report, which noted major uncertainty in how changes in climate may affect groundwater, and what resources are currently available to help support adaptation strategies.

Water resources governance, policies and legislation in Tanzania

In many river basins in Tanzania, both formal and informal institutions exist. However, how they function is not well understood, and in several cases they are ignored by the formal institutions, despite the fact that formal and informal institutions are closely linked and greatly depend on each other. As correctly put by Sokile *et al.* (2005), there are no full-fledged mechanisms as yet to better align the formal and informal institutions. In some cases, there is only superficial contact among similar institutions resulting in uncoordinated interventions, bypassing, and the duplication of efforts, while in other cases there are troublesome overlaps resulting in power struggles and collisions in operation mechanisms. Water resources management requires that these two institutions co-exist and complement each other.

Yet in another study carried out by Munishi *et al.* (2008) in the Uluguru Mountains to assess the socio-economic, cultural, and livelihood factors that influence community participation in restoration and management of water resources, they reported that conflicts and competition for water during the dry season was a major factor hampering conservation efforts in the catchments. The paper raises the fundamental question of community participation in watershed management. In many cases, communities do not see the incentive for them to conserve the water resources in a watershed. The case is worsened by the fact that even new programs and projects do not factor in incentive packages for community roles.

Another interesting case where there was some sort of institutional breakdown was reported by FAO (2005). The study was carried out in the Mkoji River sub-catchment, in the Great Ruaha River basin, and was looking at how different groups were affected by water resources management and allocation in the catchment. The results indicated that water management structures did not benefit the vulnerable groups such as the poor and the pastoralists. Even the WUAs were often dominated by middle- and upper-class landlords (FAO, 2005). In order to have a successful water resources management program, there is need to have a good understanding of the local-level dynamics, as well as the river basin and national-level policies and institutions that shape them. Therefore, an assessment of policies and institution dynamics and the water resources management linkages on various spatial scales is necessary.

In July 2002, the government issued the National Water Policy, whose main goals are to establish a comprehensive framework for sustainable development and management of water resources and for participatory agreements on the allocation of water use. The government will not be in charge of executive functions; that is, the actual delivery of the services, which are the responsibility of the Local Government Authorities. Central statements of the Policy are that "water will be subject to social, economic, and environmental criteria" and that "every water use permit shall be issued for a specific duration."

During the formulation of this water policy, Kabudi (2005) observed that for the first time in the history of legislating for the water supply in Tanzania, the issue of rural water supplies received special attention both in the policy and in the legislation proposals. However, despite that encouraging development, he observed that there were still issues that needed to be clarified on the governance and utilization of water by rural populations. These included, for example, how actively the rural population and other concerned stakeholders would be in the process.

Global literature review on water resources management

Global perspective of water resources

According to the IPCC (2007), the vast majority of the Earth's water resources are salt water, with only 2.5% being fresh water. About 70% of the fresh water available on the planet is frozen in the icecaps of Antarctica and Greenland, leaving the remaining 30% (equal to only 0.7% of total water resources worldwide) available for consumption. From this remaining 0.7%, roughly 87% is allocated to agricultural purposes (IPCC, 2007). These statistics are particularly illustrative of the drastic problem of water scarcity facing the world. Water scarcity is defined as per capita supplies of less than 1700 m3/year (IPCC, 2007).

According to the Comprehensive Assessment of Water Management in Agriculture (CA, 2007), one in three people are already facing water shortages. Around 1.2 billion people, or almost one-fifth of the world's population, live in areas of physical scarcity, while another 1.6 billion people, or almost one-quarter of the world's population, live in a developing country that lacks the necessary infrastructure to take water from rivers and aquifers (known as an economic water shortage). According to the IPCC (2007), there are four main factors aggravating water scarcity at the global level. These include: Climate change, increased urbanization, high level of consumption, and population growth.

Global water resources and climate change

In many parts of the world, variability in climatic conditions is already resulting in major impacts. These impacts are wide ranging, and the link to water management problems is obvious and profound. Climate variability is already being observed to be increasing, although there are still large uncertainties about the link to climate change (IPCC, 2007). Floods, droughts, and other extreme climate events such as hurricanes add to the major problems water managers face from population growth, urbanization, and land use changes. Every year extreme events inflict severe damage on humans and the environment in many parts of the world, but particularly so in those so-called hot spots, where the frequency of occurrence is greater, the sensitivity higher, the devastation more severe, or the communities more vulnerable. What we need to do, and can do is increase our capacity to cope with the extreme climate events, if we increase our knowledge to do so. Anticipated global warming is likely to exacerbate climate variability, and hence hydrological responses.

Both present variability and long-term, climate-change impacts are most severe in the developing world, and particularly affect the poor; that is, the segment of society least able to buffer itself against impacts. The vulnerabilities that climate variability and change create are, in consequence, a key issue in any poverty reduction program. The impacts are widespread, but there are 'hot spots' where they are particularly severe: countries, regions, and communities where the capacity to cope with, and adapt to the hydrological effects of climate variability will influence their overall development prospects.

Quantitative, spatially explicit information on groundwater in Africa is required to characterize this resource in ways that can usefully inform strategies to adapt to growing water demand associated not only with population growth but also with climate variability and change. Current continent-wide groundwater maps provide only qualitative information on the likely extent of aquifers. As such, key quantitative information outlining the dimensions of the continent's groundwater resources have, to date, remained unresolved.

Climate impacts on water demand at global scale

Expanding irrigation is helping feed the world's billions of people and may even mask global warming, but the future could bring problems. Some major groundwater aquifers, a source of irrigation water, will dry up in the future, hitting people with the double blow of food shortages and higher temperatures. Irrigation has increased because it boosts crop yields, supporting many millions of small farmers. However, concern is growing that groundwater supplies in places such as India and China may not keep up with demand. Near term and future climate predictions are essential for anticipating climate shocks and improving food security. It is important, therefore, to include irrigation in regional and global climate models so that projections of precipitation and temperature impacts can be made.

Water for normal household purposes accounts 8% of withdrawals and 6% of consumptive use in the United States (Kenneth, 1997). Water demands for gardening, lawn sprinkling, and showering are the most sensitive of these uses to climate changes. Aggregate annual domestic water use is not very sensitive to changes in temperature and precipitation. Estimates suggest that a 1% rise in temperature would increase use from 0.02 to 3.8% and a 1% decrease in precipitation would increase residential water use from 0.02 to 0.31%. Nevertheless, because they are likely to be greatest during the seasons and years when supplies are under the most stress, climate-induced increases in domestic demand can aggravate the problems of balancing supplies with demands during drought.

In Africa, several studies have been conducted globally to assess the effects of climate change on agriculture. In a study by Jones and Philip (2003), they argue that the impacts of climate change on agriculture may add significantly to the development challenges of ensuring food security and reducing poverty. High resolution methods were used to generate characteristic daily weather data for driving a detailed simulation model of maize crops in Africa and Latin America to 2055. The results indicated an overall reduction of only 10% in maize production to 2055, equivalent to losses of US$2 billion per year. They conclude by saying that climate change urgently needs to be assessed at the level of the household, so that poor and vulnerable people dependent on rainfed agriculture can be appropriately targeted in research and development activities whose object is poverty alleviation.

Climate of the West African Sahel has shown various changes, especially in terms of rainfall, of which inter-annual variability is very high. This has had significant consequences for the poor resource farmers, whose incomes depend mainly on Rainfed agriculture. The West African Sahel is already known as an area characterized by an important interaction between climate variability and key socio-economic sectors such as agriculture and water resources. In a simulation study in Niger (Mohamed *et al.,* 2002) reported that by 2025, production of millet is estimated to be about 13% lower as a consequence of climate change. In a similar study carried out in Niger, they found out that in 2025, production of groundnuts is estimated to be between 11 and 25% lower, while the cowpea yield will fall maximally by 30%. Mohamed *et al.* (2002) proposed various potential strategies to compensate for this loss including those to increase water use efficiency and to cultivate varieties that are adapted to such circumstances.

In Asia, the impacts of climate change on potential rice production have been reviewed in the light of the adaptation to climatic variability and change. According to Murdiyarso (2000), studies carried out by using process-based, crop-simulation models showed that increasing temperature may decrease the rice potential yield by up to 7.4% per degree increment of temperature. When climate scenarios predicted by GCMs were applied, it was demonstrated that rice production in Asia may decline by 3.8% under the climates of the next century. In addition, changes in rainfall patterns and distribution were also found, suggesting a possible shift of agricultural lands in the region. Furthermore, the study indicated that shifts in rice-growing areas are likely to be constrained by land use changes occurring for other developmental reasons, which may force the increased cultivation of marginal lands, and further deforestation. This should be taken into account and lead to more integrated assessment, especially in other developing countries where land use change is more a top-down policy rather than a farmer's decision.

In China, the implications of climate change for agriculture and food are very important. The country depends on an agricultural system, which has evolved over thousands of years to intensively exploit environmental conditions. Smit and Yunlong (1996) synthesized information from a variety of studies on Chinese agriculture and climate, and reported that notwithstanding the yield-enhancing effects of warming and elevated CO_2 levels, expected moisture deficits and uncertain changes in the timing and frequency of critical conditions indicate that there are serious threats to the stability and adaptability of China's food production system.

Water resources studies at the global level

Major rivers worldwide have experienced dramatic changes in flow, reducing their natural ability to adjust and absorb disturbances. Given expected changes in global climate and water needs, this may create serious problems, including loss of native biodiversity, and risks to ecosystems and humans from increased flooding or water shortages. Palmer *et al.* (2008) projected river discharge under different climate and water withdrawal scenarios. The projections indicate that every populated basin in the world will experience changes in river discharge and many will experience water stress. They conclude by saying that proactive management efforts are required to minimize risks to ecosystems and people, and may be less costly than reactive efforts taken only once problems have occurred.

In a study to evaluate the relative impact of global warming and soil degradation due to desertification on future African water resources, Feddema (1999) simulated the potential impact of global warming and soil degradation on African water resources for the 2010 –2039 time period. Results indicated that, on a continental scale, the impact of global warming will be significantly greater than the impact of soil degradation. However, when only considering the locations where desertification is an issue (wet and dry climate regions), the study reported that the potential effects of these two different human impacts on local water resources can be expected to be on the same order of magnitude. Drying associated with global warming is primarily the result of increased water demand (potential evapotranspiration) across the entire continent.

Effects of land use changes and climate on water discharge

There are abundant studies showing that an increase in forest cover can cause a decrease in water discharge due to increased evapotranspiration (Hibbert, 1967; Bosch and Hewlett, 1982). However, studies in China by Zhang and Lu (2009) reported the contrary. They noted that although the forest area in the catchment had increased remarkably since the end of the 1980s, no decrease in water discharge was observed in the Luodingjiang River. On the other hand, changing trends in temperature and evaporation variables were significant at the 0.05 significance level, suggesting their influence on the water discharge. It is well documented that watershed hydrology is affected by vegetation types, soil properties, geology, terrain, climate, land use practices, and spatial patterns of interactions among these factors. There is also a consensus that all of these factors and interactions are influenced by human activities and climate change (Knox, 2006; Tomer and Schilling, 2009).

Trends suggesting increases in precipitation and stream discharge have been documented in the Great Lakes basin (Hodgkins *et al.,* 2007) and Mississippi River basin (Lins and Slack, 2005; Kalra *et al.,* 2008) in the USA. Historical increases in base flow discharge have also been documented in the Iowa Rivers (Schilling and Libra, 2003). However, several analyses showed that increasing precipitation alone is insufficient to explain increasing discharge trends in agricultural watersheds of the Midwest (Schilling and Libra, 2003; Raymond *et al.,* 2008). Raymond *et al.* (2008) suggested that land use change and management were more important than climate changes in explaining increasing water discharge from the Mississippi River.

Therefore, water discharge is affected by agricultural land use change within agricultural systems and management. For instance, perennial transformation into annual cropping systems causes a water discharge increase. Usually, perennial crops have long roots that enable the plant to access water from the base-flow reserve as compared to annual crops that are characterized by short roots. Transformation of perennial cropping systems into annual crops results in limiting base-flow accessibility and hence the inability to extract water from the base-flow reserve. In circumstances of intact base-flow recharge, the base storage tends to increase. However, the increase may be revealed in the dry season low flows.

Knowledge gaps on water resources management in tanzania

Climate and land use impacts on water resources

The review of the literature has shown that water demand is forecasted to increase worldwide, including in those areas already experiencing high water stress. The freshwater resources have been strongly impacted by climate change and land use change. Certain land use and land cover changes, some of which are occurring at an accelerating rate, have distinct negative impacts on water resources.

The existing literature demonstrates that though progress has been made in identifying the likely consequences of various land use changes, an understanding of the areal changes, transformation, dynamics, and their associated trends are not well known in the river basins in Tanzania. Furthermore, the understanding of the effects of land use changes and associated trends for exploration of water resource changes is limited in Africa and in Tanzania in particular.

Effects of catchment land use changes on hydro-climatic relationships

The review showed that many studies have been carried out on the effects of land use change on water resources in water catchments. However, there are gaps in knowledge, particularly in Tanzania, on the effects of land use change on runoff, sediments, and runoff relationships in many river basins in the country.
Though some research assignments have been undertaken in Tanzania on spatial information systems related to water resources (for example, Kongo *et al.,* 2010; Ludovic, 2012), still there is limited knowledge in the field of satellite data use for water resources management purposes in Africa and Tanzania in particular (van Lieshout, 2009).

Meteorological and hydrologic database for water resources modelling

Many studies highlighted in the literature review are based on modeling, which requires a substantial amount of data. Both meteorological and hydrologic studies require long-term data sets of more than 30 years. Currently, existing databases on water resources and soils are either very coarse or lack the details required in planning and implementation of projects and programs. As for groundwater, the situation is worse; very few studies have been conducted. An understanding of the historical variability in water resources in Tanzania is required and this should cover the variability of surface water, ground water, rainfall, and water quality parameters. In order to enhance this understanding, tools should be developed that will assist in modelling climate change linkages with hydrological properties.

The review has shown that availability of water resources is greatly influenced by climate conditions that vary with decadal, seasonal, and inter-annual time scales. Xu (2005) recommended the importance of studies based on monthly or seasonal hydrological data. Decadal variability analysis demonstrated the usefulness of information on the decadal scale in assessing the dynamics of rainfall (Brunsell, 2010). The review has therefore shown that there is a gap in the understanding of rainfall and water discharge variability on the decadal scale in Tanzania. There are limited examples of studies using synoptic and decadal time scales.

Watershed management and approaches such as integrated watershed management are required for better performance and increased food production. Studies are required to assess the possibilities of water transfers and how best to manage the watersheds. Water use competition and conflicts in these basins are high, to the extent that new projects and programs are difficult to implement. Institutions to govern these conflicts are weak and over-stretched.

Increased water productivity under rainfed and irrigated agriculture

Irrigated agriculture, especially where the crop is from paddy fields, is blamed for using too much water. Studies in water productivity, especially those targeting the use of less water but ensuring high yields are required. In view of climate change and variability, technologies are required to counter the effects of climate change. Studies are required that will provide solutions to ensure high productivity given future scenarios of climate change in the country. Similarly, studies on irrigation development and on relevant investments are required. Currently, there is minimal research in irrigation in the country, though efforts are underway. Knowing the efficiency is one thing the issue is how we can improve water productivity. Increasing water productivity will ensure not only high yields but also the possibility of intersectoral water transfers. This is important where water is already a major obstacle to food security.

Irrigated agriculture especially for paddy production uses a lot of water and it is not true that paddy rice has to be submerged for good yields. The System of Rice Intensification (SRI), for example, advocates drying and wetting cycles, and has resulted in yields of up to 10–15 tons/ha. The SRI technology needs to be studied and adopted in Tanzania. The fact that water is applied on a drying and wetting basis means that the system can save up to 40% of water. There are other areas in irrigated agriculture that require critical analysis, and that provide answers that will propel and promote higher water productivity in irrigated agriculture.

Improved irrigation and drainage systems

Elevated concentrations of naturally occurring elements in water such as arsenic and fluoride can have catastrophic health impacts on local communities. Little is known about the distribution of these elements across Africa, and the environmental factors that control their distribution at a village level. Much more needs to be known about where these elements are likely to be at elevated levels, and how to mitigate the impacts of them on the population.

How sustainable are water points during periods of drought? Initial research has indicated that there are many factors that determine how resilient groundwater resources are to drought. Little is known about the variation of these factors, and, in particular, how renewable groundwater resources are. New research is critical to stop groundwater resources being exploited unsustainably, and to help design water supplies that are drought resistant.

On-site sanitation, although critical to the success of water projects and health of communities, can contaminate local groundwater resources. With the current focus on increasing access to sanitation, urgent research is required to ensure that this is done without compromising the quality of groundwater resources on which community water supplies depend.

Proposed research agenda and researchable issues

The following major themes are proposed as research agenda and researchable issues on water resources management in Tanzania: agricultural land and water management; land use and water resources; development of the farming environment; and water resources and climate change. The themes are briefly described below and highlight the specific objectives and possible research topics.

Agricultural land and water management in Tanzania

The first objective of this theme is to develop engineering knowledge on mechanisms involved in land and water systems and develop effective strategies for land and water utilization, management, and conservation for sustainable agricultural production in Tanzania. The first objective is to evaluate and develop strategies for managing soil and water for sustainable agriculture and environmental conservation in high and low rainfall areas in Tanzania. Associated research topics include

(a) Development of strategies for managing rainwater on agricultural land for plant growth and environmental conservation in semi-arid areas. (b) Development of land management practices that control rainfall runoff and minimize soil erosion in high rainfall highlands.

Second objective is to develop strategies for effective organization, O&M to improve productivity and environmental sustainability of small-scale irrigation schemes in Tanzania. Associated research topics include (a) Evaluation and improvement of utilization efficiency of irrigation water. (b) Development of systems for tree crop irrigation. (c) Evaluation and improvement of environmental sensitivity and benefits of irrigation schemes.

Third objective is to develop techniques for effective and efficient rainwater utilization in order to increase rice yields under RWH rice systems. Research will be required to address the following: (a) Develop tools to assist planners in making sound decisions on how the water resources should be sustainable utilized. (b) Assess policies and institution dynamics and the water resources management linkages under various spatial scales.

Natural resources and sustainable environment in Tanzania

The first objective of this theme is to assess the suitability of natural resources, especially different types of land being mapped as land units for selected and specified land use types. Land evaluation scenarios must be developed, which indicate the natural properties and the potential constraints for land use types. In addition, it is prudent to look into the following research topics: (a) Establishment of an ecological and environmental monitoring system for land degradation and desertification processes. (b) Restoration and conservation of the degraded watersheds to improve household food security, poverty reduction for better livelihoods, and a sustainable environment.

The second objective of this theme is to analyze the agro-ecological and socio-economic interactions of variables at farm level to give insight into possible and necessary improvements in existing ways of farming. Research will be required to analyze the farming environment and land use practices to identify constraints on farm-level performance and to derive recommendations with regard to the physical and institutional infrastructure.

The third objective of this theme is to develop experimental methods to test the adapted technology at the farm level as a contribution to designing sustainable land use systems. Research will be required to develop research methodologies to translate farm-level constraints into testable technologies in Tanzania and to test these technologies under the conditions of an experimental station as well as on farms.

The fourth objective of this theme is developing strategies for minimizing environmental degradation and pollution resulting from agricultural operations and processing. Therefore, research will be required to address:

(a) Assess environmental degradation resulting from inappropriate land use and management.
(b) Assess environmental degradation resulting from use of agricultural chemicals/fertilizers in agricultural production systems (rainfed/irrigated).
(c) Development of effective strategies for pollution control.

Water resources and climate change in Tanzania

Under this theme, research will be required to address key climate–water interactions. Research topics will include the following: (a) Develop tools that will assist in modelling the surface–groundwater interactions. (b) Develop tools that will assist in modelling the surface water–climate linkages, groundwater–climate linkages. (c) Develop tools that will assist in modelling the water quality–climate-change linkages. (d) Assess the effects of climate change and variability on environmental flows, water balance, and its effects on crop production.

Irrigated agriculture

Under this theme, research will be required to address the following topics: (a) Assessment of drip irrigation systems for grape production, climate-change adaptation, and improved livelihoods in Tanzania. (b) Assessment of the concrete pedal pump for micro irrigation systems for water and crop productivity and climate-change adaptation. (c) Develop models that can assess the marginal values of water including scenarios as well as taking into account the risks of water transfer including virtual water. (d) Assess the effect of evaporation on water productivity in open canal irrigation systems.

These include among others: (a) Assessment of drip irrigation systems for grape production, climate change adaptation, and improved livelihoods. (b) Assessment of a concrete pedal pump for micro irrigation systems for water and crop productivity and climate change adaptation. (c) Economic analysis of different irrigation systems. (d) Effect of evaporation on water productivity in open canal irrigation systems.

Groundwater resources

Under this theme, research will be required to address the following topics: (a) research is required in Tanzania to ensure that access to sanitation is done without compromising the quality of groundwater resources on which community water supplies depend. (b) How resilient are groundwater resources to drought? Little is known in Tanzania about the distribution of these elements and the environmental factors that control their distribution on the village level. Much more needs to be known about where these elements are likely to be elevated and how to mitigate the impacts of them in the population.

Water resources governance

Under this theme, research will be required to address the following topics: (a) Urgent research is required to develop land-tenure arrangements that are attracting long-term commitments of land resources for improving the productivity through irrigation. (b) The relationship and role of formal and informal institutions dealing with water in Tanzania is not well understood. This is an area that needs further research.

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