Universidade do Minho
Escola de Engenharia

Muhammad Tajuri Ahmad

Assessment of sustainable efficiency (Sefficiency) and water allocation under uncertainty in Kano River basin

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Doctoral Thesis
Civil Engineering

Work performed under the supervision of
Prof. Doutor Naim Haie

April, 2018

STATEMENT OF INTEGRITY

I hereby declare having conducted my thesis with integrity. I confirm that I have not used plagiarism or any form of falsification of results in the process of the thesis elaboration.

I further declare that I have fully acknowledged the Code of Ethical Conduct of the University of Minho.

University of Minho, April, 2018

Full name: Muhammad Tajuri Ahmad

Signature: ____

Acknowledgement

I am grateful to my supervisor, Professor Doutor Naim Haie, for his generous guidance, wisdom, and support in several ways. It has been a pleasure to work with you. I would like to thank all the teaching staff of Civil Engineering department, especially Assoc. Prof. Daniel Oliveira, Prof. Maria Madalena Araújo, Assoc. Prof. Rosa Vasconcelos, Assoc. Prof. Júlio Silva, Prof. Luís Bragança, and Prof. Antonio Gomes Correia. I also thank Rosário Pereira and Mariana Moreira (Secretariado Programa Doutoral em Engenharia Civil) for all the help.

Also, many thanks to Dr. Haw Yen of Texas A & M University, US for his great help in reviewing my thesis. Aiuba Suleimana, Hamid Maljaee and Elisabete Rodrigues Teixeira, I appreciate all the support. I would also like to thank the staff and management of Hadejia-Jama’are River Basin Development Authority, Kano State Water Board, Kano State Ministry of Environment, Kano State Ministry of Water Resources and the farmers of Kano River Irrigation Project especially Abdulkadir Abdulmalik.

I gratefully acknowledged the financial support received from the Federal Government of Nigeria Tertiary Education Trust Fund under the TETFund 2014 AST & D Intervention for Kano University of Science and Technology, Wudil, Kano, Nigeria for Ph.D. Overseas Training.

To my mother and my family, I couldn’t have done this without your prayers, love, patience and support. Thank you for everything. I love you all. To all my friends and my colleagues. To my father, may his gentle soul rest in peace.

Abstract

The ever-increasing population and climate change have placed a considerable pressure on Kano city water supply (KCWS) and Kano River Irrigation Project (KRIP), major water users on Kano River, the most upstream tributary of Yobe River flowing directly to Lake Chad which is an important transboundary basin in West Africa. Under water scarcity and competing water uses, improved knowledge of the performance of water use systems (WUS) is essential for policy formulation and sustainable development of water sector. This study is carried out in semi-arid Kano River basin of Nigeria, where water is a limiting factor, but a comprehensive knowledge on the performance of different water users across the basin are lacking. The main objective is to assess the performance of main water users and provide a thorough analysis of the impacts of drivers of change on their performances using new and innovative methodological framework called Sefficiency (Sustainable efficiency). However, crop requirements were estimated using CROPWAT 8.0.

In evaluating KRIP, two major stakeholders were contacted, namely, farmers and water managers and their views on the value of water flows were registered through interviews. The results indicated that useful consumption relative to effective consumption of farmers is significantly lower than management, showing a higher relative consumptive impact on both KRIP and Kano River. Also, the useful outflow per unit of useful inflow is lower according to the farmers relative to the managers. Classical efficiency in use globally gives much lower values than meso-efficiency.

The synthesis of the results for Kano River model reveals that effective consumption that is useful consumption is lower relative to beneficial consumption which is an indication of pollution that increases effective consumption and consequently decreases efficiency. The difference between beneficial inflow and beneficial consumption indicated that water consumption is through non-reusable water flow paths that do not consider quality, i.e., evaporation. Moreover, beneficial consumption efficiency is lower than inflow efficiency due to a combination of relatively high return flow and pollution impact. The low value of MicroE$_s$ suggests that the WUS itself is not efficient in using its water resources.

The temporal changes in the performance of the WUSs according to uncertainty related to the drivers of change were also explored as part of the system analysis. The performance of KRIP and Kano River were degraded significantly under projected population and future climate conditions. However, Kano River is less sensitive to global warming impacts suggesting that population growth is the dominant driver of change. Moreover, cumulative effects of population and climate change impact in Kano River basin resulted in a reduction of downstream water by 70% to below the recommended volume. Generally, potential demands for water will far exceed the available supply by 2050 thereby affecting water allocation.

The study concludes that the regional water managers have a much broader view of water needs and impacts, such as pollution and groundwater depletion, than farmers, and consequently, can better relate useful flows and (effective) consumptions for sustainable management, including technological investments. Water quality has a dominant influence on the performance of Kano River model under population growth. The quantitative efficiency values show decreasing trends mostly due to the assertion that evaporation have less beneficial value under climate change scenario. For KRIP, quantitative meso-efficiency values for climate change show increasing trends because water quality is not considered and relative quantities remain the same while beneficial consumption increases. Increasing the effective consumption in terms of decreasing the pollution caused by anthropogenic activities is the pathway to achieving better results.

The study recommends that Kano River basin should be properly managed by employing Sefficiency framework, which puts water as the central issue for policy making. It would be helpful to improve the set of data using remote sensing and GIS and use of smart systems particularly for improving water balance flow paths and their qualities. The Sefficiency model application demonstrated in this study should be extended by testing other “what if” scenarios (e.g., water user associations, before and after the TRIMING intervention project funded by World Bank, and wastewater treatment plants). Our results point to the need for in-depth studies to understand the dynamics of the trade-offs that influences Sefficiency.

Resumo

O aumento da população e as mudanças climáticas têm colocado uma pressão considerável sobre o abastecimento de água da cidade de Kano (KCWS) e Projeto de Irrigação do Rio Kano (KRIP), maior usuário de água do Rio Kano, o Rio Yobe afluente mais a montante de que flui diretamente para o Lago Chade, que é uma importante bacia transfronteiriça na África Ocidental. A escassez e usos competitivos de água, um conhecimento melhorado do desempenho dos sistemas de uso da água (WUS) é essencial para a formulação de políticas e o desenvolvimento sustentável do setor de água. Este estudo foi realizado no Rio Kano que é bacia hidrográfica da Nigéria, onde a água é um fator limitante, mas falta um conhecimento abrangente sobre o desempenho de diferentes usuários de água em toda a bacia. O principal objetivo é avaliar o desempenho dos principais usuários de água e fornecer uma análise completa dos impactos dos fatores de mudança. em seus desempenhos usando um novo e inovador quadro metodológico chamado Sefficiency (eficiência sustentável). No entanto, os requisitos de cultivo foram estimados usando o CROPWAT 8.0.

Na avaliação do KRIP, foram contactados os principais intervenientes, nomeadamente agricultores e gestores da água, e as suas opiniões sobre o valor dos fluxos de água foram registadas através de entrevistas. Os resultados indicaram que o consumo útil relativo ao consumo efetivo dos agricultores é significativamente menor do que o manejo, mostrando um maior impacto relativo de consumo tanto no KRIP quanto no Rio Kano. Além disso, a vazão útil por unidade de entrada útil é menor de acordo com os agricultores em relação aos gerentes. A eficiência clássica em uso globalmente dá valores muito menores do que a mesoeficiência.

A síntese dos resultados para o modelo do rio Kano revela que o consumo efetivo que é o consumo útil é menor em relação ao consumo benéfico, o que é uma indicação de poluição que aumenta o consumo efetivo e consequentemente diminui a eficiência. A diferença entre fluxo de entrada benéfico e consumo benéfico indicou que o consumo de água é através de caminhos de escoamento de água não reutilizáveis que não consideram a qualidade, ou seja, a evaporação. Além disso, a eficiência do consumo benéfico é menor do que a eficiência do fluxo de entrada devido a uma combinação de fluxo de retorno relativamente alto e impacto da poluição. O baixo valor

de MicroEs sugere que o próprio WUS não é eficiente no uso de seus recursos hídricos.

As mudanças temporais no desempenho das WUSs de acordo com a incerteza relacionada aos vetores de mudança também foram exploradas como parte da análise do sistema. O desempenho do KRIP e Rio Kano foram degradados significativamente pela projeção da população e condições climáticas futuras. No entanto, o rio Kano é menos sensível aos impactos do aquecimento global, sugerindo que o crescimento populacional é o principal fator de mudança. Além disso, os efeitos da população e alterações climáticas acumulam impactos na bacia do rio Kano e resultou numa redução de água a jusante por 70% para um valor inferior ao volume recomendado. Geralmente as demandas potenciais por água na bacia excederão em muito a oferta disponível até 2050, afetando a alocação de água.

O estudo conclui que os gestores regionais de água têm uma visão muito mais ampla das necessidades e impactos das águas, como poluição e esgotamento das águas subterrâneas, do que os agricultores e, consequentemente, podem relacionar melhor fluxos úteis e consumos (efetivos) para manejo sustentável, incluindo investimentos tecnológicos. A qualidade da água tem uma influência dominante no desempenho do modelo do rio Kano sob o crescimento da população. Os valores quantitativos de eficiência mostram tendências decrescentes principalmente devido à afirmação de que a evaporação tem valor menos benéfico no cenário de mudanças climáticas. Para o KRIP, os valores quantitativos de meso eficiência para as mudanças climáticas mostram tendências crescentes porque a qualidade da água não é considerada e as quantidades relativas permanecem as mesmas enquanto o consumo benéfico aumenta. Aumentar o consumo efetivo em termos de diminuir a poluição causada por atividades antropogénicas é o caminho para alcançar melhores resultados.

O estudo recomenda que a bacia hidrográfica do rio Kano seja administrada de forma adequada, empregando o quadro de eficiência, que coloca a água como a questão central para a formulação de políticas. Seria útil melhorar o conjunto de dados usando o sensoriamento remoto e o SIG e o uso de sistemas inteligentes, especialmente para melhorar os caminhos de fluxo do balanço de água e suas qualidades. A aplicação do modelo de eficiência demonstrada neste estudo deve ser estendida testando outros cenários (por exemplo, associações de usuários de água, antes e depois do projeto de intervenção TRIMING financiado pelo Banco Mundial e estações de tratamento de

águas residuais). Nossos resultados apontam para a necessidade de estudos aprofundados para entender a dinâmica dos compromissos que influenciam a eficiência.

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Glossary of Terms

CE	Classical efficiency
CRW	crop water requirements
EE	Effective efficiency
GCMs	Global Circulation models
GIS	geographic information systems
ha-m	Hectare-metre
HJRBDA	Hadejia-Jama'are River Basin Development Authority
HNWCP	Hadejia-Nguru Wetland Conservation Project
HVIP	Hadejia Valley Irrigation Project
IMWI	International Water Management Institute
IWRM	Integrated Water Resources Management
KCWS	Kano City Water Supply
KNSWB	Kano State water board
KRB	Kano River basin
KRIP	Kano River Irrigation Project
m^3/s	Cubic meter per second
Mm^3	Million cubic meters
NASA	National Aeronautics and Space Administration
NIMET	Nigerian Meteorological Agency
NPC	National Population Comission
PIs	Performance indicators
PP	percentage points
RKR	Ruwan Kanya Reservoir
Sefficiency	Sustainable efficiency
Sustainable Development Goals	SDGs
TIE	Technical irrigation efficiency
UN	United Nations
UNESCO	United Nations Educational Scientific and Cultural Organization
WaPs	water flow paths
WaTs	water flow path types
WHO	World Health Organization
WP	Water productivity

WUAs	water user associations
WUE	Water use efficiency
WUS	Water use system

CHAPTER ONE
INTRODUCTION

1.1 General introduction

Water impacts virtually everything humans care about (Loucks, 2017). It shapes the earth’s landscape through soil erosion, transportation and deposition by rivers, glaciers, and ice sheets; through evaporation, water drives the energy exchange between the land and atmosphere, thus controlling the Earth’s climate (Falkenmark, 1997). Water also improves health, combats poverty and ensures environmental sustainability. Hence one of the most crucial means to development is a proper and sustainable development of water resources. In a sense all the benefits that humanity gets from land use and energy consumption are secondary to water use, meaning that water is one of the central issues, if not the centre itself, that the design and management of any system have to consider (Haie, 2016).

In most developing sub-Sahara African countries, including Nigeria, the intensifying effect of population growth, economic development and climate change contributes to the increasing pressure on the already threatened and scarce water resources exacerbating the already tenuous problem of inter-sectoral water competition. These factors limit the availability of water for food production and threaten food security in many developing countries (Amegbeto, 2017) and contribute to absolute water scarcity which affects the majority of the population. Furthermore, climate change impact affects the availability and quality of both surface and groundwater, and affect agricultural production and associated ecosystems (Birkenholtz, 2017; FAO, 2015; Faramarzi et al., 2013; Fischer, Tubiello, van Velthuizen, & Wiberg, 2007; Hall, Dawson, Macdiarmid, Matthews, & Smith, 2017; IPCC, 2014; Niang et al., 2014; Raje & Mujumdar, 2010; Vorosmarty, Green, Salisbury, & Lammers, 2000).

Agriculture uses a large part of freshwater withdrawals with irrigation amounting to 70% of total anthropogenic use (Fischer et al., 2007), and the ratio is even higher in the majority of least developed countries (FAO, 2011). For example, out of the 12,475 Mm^3 (total annual water withdrawal in Nigeria of for the year 2010, agriculture is the sector withdrawing the most significant share of water of 5,510 Mm^3 (44 percent) with irrigation made up of 4,549 Mm^3. Municipal and industrial water withdrawal was at 5,000 Mm^3 (37 percent) and 1,965 Mm^3 (17 percent) respectively (Butler et al., 2017). Unaccounted for water was the remaining 3 percent. Approximately half of agricultural withdrawals reach the crops (used for crops production), and the remaining is lost through leakages and evaporation in irrigation infrastructures (Fischer et al., 2007). The excess amount is released because of poor water control, inefficient irrigation systems with leaky conveyance and distribution, poor on-farm water management practices, etc. However, some part is lost to saline groundwater or poor quality drainage water (Dejen, Schultz, & Hayde, 2012), although it can be recovered and use downstream (Ghahroodi, Noory, & Liaghat, 2015; Haie & Keller, 2012). According to FAO (2011), more than 60% of all water withdrawals was estimated to flows back to local hydrological systems by return flows to rivers or groundwater. The remaining part is considered consumptive water use through evaporation and plant transpiration.

Although the rate of water withdrawal for both municipal and agricultural use has increased over the last few decades and will continue to increase, there are adequate land and water resources available to satisfy global food demands in the next 50 years. But only if water is managed more efficiently in agriculture (de Fraiture, Molden, & Wichelns, 2010; de Fraiture & Wichelns, 2010). This depicts that increasing water systems performance in terms efficiency remains the only possible option for realizing the SDGs. According to UN-Water (2012)), agricultural water consumption is expected to increase by about 20% globally by 2050 without improved efficiency measures. Furthermore, water-use efficiency improvements are considered instrumental in addressing the projected 40% gap between demand and supply and mitigating water scarcities by 2030 (UNEP, 2011).

Improving the performance of urban and irrigation schemes through various interventions is considered a vital issue for addressing the pressure on water resources. The performance of water resource systems and water use activities are often expressed in terms of indicators. Indicators play an essential role in spreading information, transforming complex scientific data into few and understandable numbers (Bastiaanssen et al., 2001; Brown et al., 2015; Ermini, Ataoui, & Qeraxhiu, 2015; UN-Water, 2006), notify decision makers and report on trends and fulfil the international obligation (Marinus Gijsberthus Bos, Burton, & Molden, 2005; Vilanova, Magalhães Filho, & Balestieri, 2015).

1.2 Overview of water resources management in Nigeria

Water resources management encompasses various sectors such as irrigated agriculture, municipal water supply, hydroelectric power, flood control, ecosystems, navigation, etc.), each with a different array of management objectives and guiding legislation and regulations. In Nigeria water resources management is facilitated under the following governmental organizations. Nigerian Government Decree 101 of 1993 confers all rights and control of Nigeria's water resources in the federal government. It confers on the Federal Government represented by the Federal Ministry of Water Resources (FMWR) the responsibility for controlling the use of both surface and groundwater resources traversing more than one state throughout the Federation with eleven River Basin Development Authorities (RBDAs) mandated with the power of administration within their area of jurisdiction (Figure 1). For a detailed discussion on the establishment, functions, rights and responsibilities in water resources management in river basins in Nigeria refer to Akpabio (2007) and Akpabio (2008).

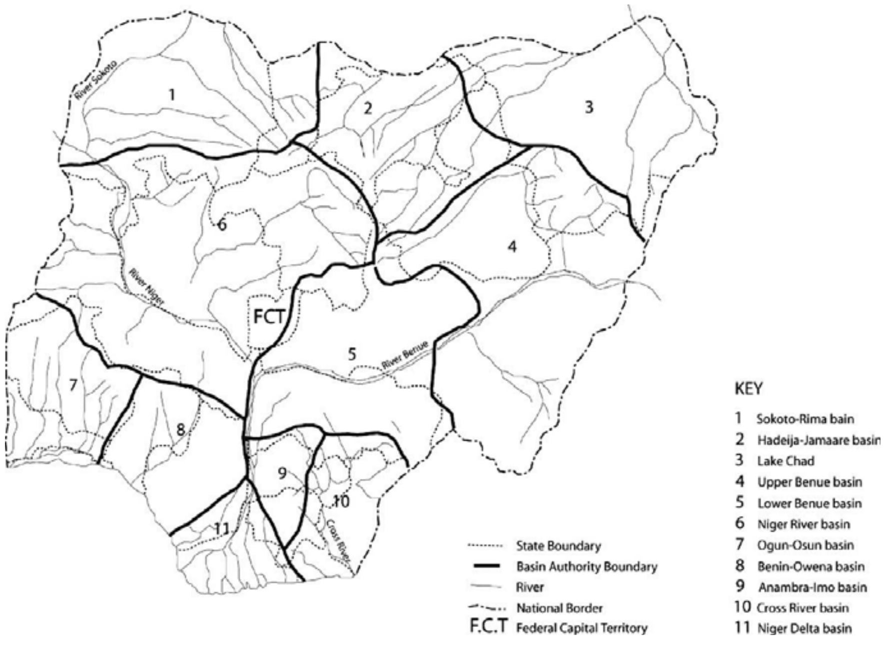

Figure 1 Map of Nigeria showing eleven RBDAs

The eleven river basin development authorities (RBDAs), their area of operation and headquarters are presented in Table 1 below.

Table 1 River Basin Development Authorities in Nigeria

s/no.	Name of authority	Area of operation	Headquarters
1.	Anambra–Imo River Basin	The whole of Anambra, Abia, Enugu, Imo and Ebonyi States	Owerri
2.	Benin–Owena River Basin	The whole of Edo, Ekiti, Ondo States and area of Delta State drained by the Benin, Escravos, Forcades and Ramos Rivers Creek' Systems	Benin
3.	Chad River Basin	The whole of Borno and Yobe States and area of Adamawa State drained by the Yedseram and Goma River Systems	Maiduguri
4.	Cross River Basin	The whole of Akwa Ibom and Cross River States	Calabar
5.	Hadejia–Jama'are River Basin	The whole of Jigawa, and Kano States, and the area of Bauchi State drained by the Misau and Jama'are River System	Kano
6.	Lower Benue River Basin	The whole of Benue, Nassarawa and Plateau States	Makurdi
7.	Niger Delta Basin	The whole of Rivers, Bayelsa and part of Delta States	Port Harcourt
8.	Ogun-Oshun River Basin	The whole of Lagos, Ogun, Osun and Oyo States	Abeokuta
9.	Sokoto–Rima River Basin	The whole of Katsina, Kebbi, Sokoto and Zamfara States	Sokoto
10.	Upper Benue River Basin	The whole of Gombe and Taraba States and the area of Bauchi State drained by the Gongola River system and the whole of Adamawa excluding the area drained by the Yedseram River system	Yola
11.	Upper Niger River Basin	The whole of Kwara, Kogi, Niger and Kaduna states and the Federal Capital Territory	Minna

Kano River basin is a sub-catchment of Hadejia River under the jurisdiction of Hadejia-Jama'are River Basin Development Authority (HJRBDA). The operational area of HJRBDA comprises the upper reaches of the catchment falling within northern parts of Bauchi State, and the whole of Kano and Jigawa states. Presently, the following irrigation projects have been developed by HJRBDA in Kano River basin: Tiga, Ruwan Kanya and Challawa Gorge reservoirs, as well as Kano River Irrigation Project (KRIP).

State Ministries of Agriculture and Natural Resources (SMANR) and Ministries of Water Resources (SMWR) jointly play similar roles on land and water resources management to those of FMARD and FMWR respectively at the State level with some modifications. State Water Boards (SWB) have the responsibility for the treatment and delivery of municipal and rural water supply and sanitation lies with the State governments. Each has agency/agencies to manage and develop the systems. They are also involved in water resource development and monitoring and have some reservoirs, treatment plants, and a network of hydrological data collection stations.

1.3 Structure of the thesis

This thesis comprises of seven chapters, whose brief description is as follows. Chapter 1 highlights a general overview of management of urban water supply and irrigated agriculture in Nigerian perspective, structure of the thesis, background and objectives, and research framework. Chapter 2 gives a state-of-the-art literature review on the performance assessment and indicators. Chapter 3 highlights general research methodology. Chapter 4 presents the results of a comparative performance assessment in KRIP using two major actors in the schemes, a discussion of differences, and issues related to these differences. Chapter 5 presents an evaluation of the performance of Kano River model. Chapter 6 is about the case scenarios and sensitivity analysis. In this chapter, the impacts of climate change on Kano River model performance as well as effects of demand volume changes due to population has been considered in the formulation of different scenarios. Chapter 7 presents the general conclusions and the direction for future research.

1.4 Background and objectives

1.4.1 Need for performance assessment in water systems

Water management along river basin in semi-arid regions is a complex issue because there is a limited supply of water to satisfy the demand of all the sectors and environmental needs. Management of water resources has become more intricate, and drivers of change such as population growth, climate change, and food production demand are intensifying. Increasing sustainable access to safe water and sanitation for all by the year 2030 is part of Sustainable Development Goals (SDGs) (Pisano, Lange, & Berger, 2015) and is unlikely to be achieved primarily in developing countries, such as Nigeria (Ahmad & Daura, 2017). Therefore, evaluation of water resource system (WRS) becomes fundamental in improving the performance of the systems to achieve sustainability of limited freshwater resources.

Performance assessment of water resource systems is fundamental in developing water management and allocation policies. However, for sustainability water allocation should consider three fundamental principles: equity, efficiency, and sustainability (Haie & Keller, 2014; Wang, Fang, & Hipel, 2008). Water allocations merely based on water rights approach or economic benefits usually do not make efficient use of water for the whole river basin (Wang et al., 2008).

1.4.2 Description of Kano River basin and problem statement

Northern Nigeria is part of the semi-arid region of Africa known as the Sudan Sahel, and many of its parts suffer from water scarcity issues. Kano River basin is situated in this region. There are two principal rivers in the basin; Kano and Challawa Rivers that meet to form the Hadejia River which flows eastwards to Lake Chad, which is an essential transboundary basin in West Africa. The rivers are controlled by Tiga and Challawa dams constructed upstream. In fact, Goes (1999) stated that 80% of the flow in the Hadejia River is controlled by Tiga and Challawa dams built upstream.

The geologic formation of the area consists of mostly impermeable basement complex rocks (Goes, 1999). The mean annual rainfall ranges from about 1000 mm in the basin to 400mm in the middle part of the broader HJKY basin and less than 300 mm near Lake Chad. The mean annual temperature is around 25ºC in the basin. Thompson & Hollis (1995) stated that almost 80% of the total annual flow is in August and September with periods of no flow in October to April. Evaporation rates are about 2,100 mm annually. The population supported by the basin was estimated to be around 3 million in 2015 (NDHS, 2013). The traditional farming system in the basin is predominantly rain-fed. The most extensive irrigation scheme in the basin is Kano River Irrigation Project (KRIP) supplied by Tiga Dam, the most significant dam in the basin, which was completed in 1974. Different water demands in Kano city regarding domestic, commercial and some industrial needs are met using water from Tiga and Challawa dams. The responsibility of providing water is vested in Kano State water board (KNSWB). However, the agency could only provide 60% of the total water demand for the city.

Nonetheless, the fact that northern Nigeria experiences periodic droughts (Barbier, 2003; Ko & Tarhule, 1994), water scarcity could also be as a result of lack of an integrated water resources management, climate change impact, population growth and increased demands around the river basin (Bangash, Passuello, Hammond, & Schuhmacher, 2012; Chiroma, Kazaaure, Karaye, & Gashua, 2005; Onyenechere, 2010; Vorosmarty et al., 2000; Yahaya, Ahmad, & Abdalla, 2010). Furthermore, issues of water allocation among various users (irrigation, urban supply and environmental flows) could be another factor (Chiroma, Kazaaure, Karaye & Gashua, 2005; Goes, 2002; Yilmaz & Harmancioglu, 2010). (Goes, 2002) pointed out that the potential water requirements in the whole basin (Hadejia-Jama'are River basin) exceed the water availability in a mean year. Degradation of water quality is another problem in the basin.

The water issues of concern as identified in Kano River Basin are as follows:

i. Poor coordination: In Nigeria generally, there is a perceived lack of multi-sectoral coordination and support in the research and development of water resources. KNSWB, Kano state ministries of agriculture and water resources, Federal ministry of water resources and HJRBDA all have responsibilities in the management of basin's water resources. Some responsibilities overlap, and sometimes various institutes have been taking unilateral decisions without efficiently coordinating the various development efforts. The unilateral decision by Kano state government of constructing hydropower station at Tiga dam (HaskoningDHV, 2015) is an example of uncoordinated surface water uses which raises concern for water availability for KRIP. It was pointed out that all major and small schemes and dams were developed in this way (Goes & Zabudum, 1997) neglecting the negative impacts of the upstream developments on downstream users during the development process of these projects.

ii. Water allocation problems: the uncoordinated developments in the basin due to increasing demands for water leads to an inequitable water distribution and environmental damage. The dam lack adequate operational information and are (in most cases) operated based on the rule of thumb, for example, KCWS augments the dry-season flow because a relatively high minimum river flow is required before sufficient water enters the intake-works. (Chiroma, Kazaaure, Karaye & Gashua 2005). This help in unsustainable releases from Tiga dam which significantly deplete the limited resources and increase its risk of failure, in terms of not meeting their supply commitments and their inability to release wet season flows to downstream users.

iii. Degradation in water quality: drainage water from KRIP may contain insecticides and nutrients from fertilizers especially rice and other crops that require a high dosage of fertilizer. Wastewater from Kano city and industrial sludge and liquid waste are discharge in open drains, sewer systems and watercourses without treatment. It has been observed during field survey that there is a drainage canal on Challawa River, near KCWS intake no. 6, which empties thick black sludge into the river around *Dandanko* village (Figure 2). The waste treatment facilities that do exist are either inadequate or not functioning (Goes, 2005). The waste by-products from tanneries have high concentrations of the heavy metals chromium and cadmium. Pollution due to urban agriculture has been described to pose a risk to food security in Kano (Dawaki, Dikko, Noma, & Aliyu, 2013).

iv. Poor stakeholders' participation in decision making processes, planning, implementation and evaluation of hydraulic projects among others (Goes, 2005).

Figure 2 Industrial effluents entering Challawa River

1.5 Research Framework

1.5.1 Research motivation

Irrigation and urban water supply use a significant part of the available water resources in Kano River basin. The over-use of water by these sectors is already causing severe water shortage that significantly affects the livelihoods of downstream users, and therefore has an essential role in the efficient use of water resources in the basin. Thus, concerns about water scarcity should pay more attention to these sectors.

Formulating policies for water systems management require an understanding of how they are currently used, in order words, their present performance. However, evidence on the aspects of water resources management in the developing countries including Nigeria has been thin especially in the study area. For instance, not much is known of the efficiency, except for viability of Nigeria's water management institutions in very few reported cases from the Northern region (Akpabio, 2008).

Therefore, a proper basin-wide demand control policy has become essential. Policymakers have to decide on quantities of water to be allocated to the large formal users, and the consequences of the allocation on the amount of water remaining for uses downstream has to form part of the decision making process. This could be achieved by evaluating the present and future performances of the sectors using different scenarios.

1.5.2 Research aim and objectives

The main aim of this research is to assess the performance of major water users in Kano River basin using performance indicator of Sustainable efficiency (Sefficiency).

The specific research objectives are as follows:

1. To evaluate the current baseline hydrological conditions of the river basin.
2. To measure the performance efficiency of the two principal water users in the river basin using the concept of Sefficiency.
3. To gain insight into the effectiveness of Sefficiency, its ability and limitation in presenting the reality of river basin in the context of integrated water resources management.
4. Develop scenarios for the future water allocation schemes according to uncertainty related to population and climate changes.
5. To develop a model that will quantify water allocation to different sectors (KRIP and KCWS) to increase efficiencies and to reconcile the conflicting demands.

1.5.3 Contribution of the proposed research

This PhD research contributes directly to understanding the present situation in Kano River basin. It presents the first and most recent performance assessment of the water users in the basin. To the best of knowledge of the researcher, there are no published studies that assess the performance of any water user in the study area. In general, this research contributes to improving understanding of basin-scale performance assessment exhibited in macro, meso and micro scales in a semi-arid basin which is data scarce. The knowledge generated by this study is helpful to serve as an input in the sustainable management of water resources in a river basin context for the Kano

River Basin, and similar regions of Nigeria and elsewhere. It could also serve as a foundation for further research in the basin and Nigeria in general.

CHAPTER TWO
LITERATURE REVIEW

This chapter is devoted to explaining a few key topics relevant to this research and presenting the accomplishments reported in the literature. There remains an amount of obscurity in defining efficiency of irrigation systems and other water-related nomenclature. Irrigation professionals, hydrologists and plant scientists use several terms for evaluating the performance of agriculture and definitions remain unclear. Therefore, the first three sections are used to elaborate on explaining the terms and how they relate at different spatial scales. The last section provides a review of the various techniques and approaches for assessing performance in urban and agricultural domains.

2.1 Introduction

Water management along river basin in semi-arid regions is a complex issue because there is a limited supply of water to satisfy the demand of all the sectors and environmental needs. Management of water resources has become more intricate, and drivers of change such as population growth, climate change, and food production demand are intensifying. Increasing sustainable access to safe water and sanitation for all by the year 2030 is part of Sustainable Development Goals (SDGs) (United Nations, 2015) and is unlikely to be achieved primarily in developing countries, such as Nigeria.

Many factors may be responsible for this. van der Bruggen, Borghgraef, & Vinckier (2010) identified factors leading to water supply problems in urbanized regions in developing countries as; high rate of population growth, lack of investments in water supply infrastructure and unavailability of water sources. Hamid, Mohamed & Mohamed (2011) identified mismanagement relative to the performance of water systems as the reason behind their malfunctioning. Furthermore, poor irrigation water management associated with water scarcity has been the major reason for underperformance in most small-scale irrigation schemes (Yohannes, Ritsema, Solomon, Froebrich, & van Dam, 2017). Hence, evaluating water use system to improve its performance for optimal productivity in the context of increasing demand for food and limited freshwater resources becomes crucial or a part of standardized procedures (Burt, Clemmens, Solomon, Howell & Strelkoff, 1999; Labadie, 2004). Better efficiency for water resources systems is recommended as one of the most important responses to climate change, unsustainable development and water shortage. And if that is not the case, a diagnosis can be carried out in order to detect the problems arising and to propose adequate solutions (Dembele, Yacouba, Keïta & Sally, 2012).

The efficiency of water resources is essential, just as important is the terminology that describes it (Haie & Keller, 2014). In other words, terminology in the concepts of efficiency is crucial just as the performance assessment itself. Over time, water professionals have debated over the terminology issues and the findings are consistent with one another. For instance, Pereira, Cordery & Iacovides (2012) and Van Halsema & Vincent (2012) demonstrated the uncertainties in applying terms between and within water resources management and other groups of users, and it's consequence on poor use of water. In line with that, several authors have advocated for unambiguous and consistent languages, descriptions and interpretations that could be used by various international institutions and professionals in the agricultural, urban and environmental domains (Haie & Keller, 2014; Heydari, 2014; Lankford, 2006; Pereira, Oweis, & Zairi, 2002; Pereira et al., 2012; Perry, 2011). Otherwise, these concepts are not neutral, and policies based on these notions might affect poor people negatively, thus creating more poverty instead of less (Boelens & Vos 2012; Wichelns 2013).

With regard to the research conducted in the field of water systems management, several authors introduced the concepts of performance efficiency (Bos, 1997; Bos, Murray-Rust, Merrey, Johnson, & Snellen, 1994; Burt et al., 1997; Frederiksen & Allen, 2011; Haie & Keller, 2012; N Haie & Keller, 2008; Keller & Keller, 1995; Mateos, 2008; Molden & Gates, 1990; Seckler, Molden, & Sakthivadivel, 2003). They did so by defining specific indicators that express the state of different elements of a system quantitatively. These include classical efficiency, effective efficiency, net efficiency and sustainable efficiency (Sefficiency) that incorporate water reuse, the difference between total water use and water consumption, the effect of use location and water quality and usefulness criterion. Other authors introduced concepts of efficiency that assess the hydraulic performance of a real water supply (Ermini et al., 2015).

However, any robust indicator should be based on sound principles and scientific formulations (Bos et al., 1994; Brown et al., 2015; UN-Water, 2006) such as water balance. Otherwise, flawed water planning and management approaches could only aggravate water scarcity (Gain & Giupponi, 2015) especially when water quality issues are involved (Ayars & Schoneman, 2006; Haie & Keller, 2014).

In the case of system failure, authors (Ajami, Hornberger, & Sunding, 2008; Asefa, Clayton, Adams, & Anderson, 2014; Hashimoto, Stedinger, & Loucks, 1982; Jain & Bhunya, 2008; Sandoval-Solis, 2011) employed the concept of reliability, resiliency, vulnerability and sustainability index. They analysed system concerning its probability of success or failure, the rate of recovery from undesirable states and the expected consequence of being in that for long periods. Each index assesses a different aspect of the water supply system, and as such they are complementary.

Field experiments have been extensively used to evaluate water management practices, albeit they are often expensive, time-consuming and site-specific (Jiang, Xu, Huang, Huo, & Huang, 2015). Remote sensing is new lines of research that offer good examples of methods for improving water management in irrigation, although not all water users and administrators in irrigable areas throughout the world can afford this type of tool (Tarjuelo et al., 2015). Related to this, Gomo, Senzanje, Mudhara, & Dhavu, (2014) identified resource constraints and the small size of individual irrigated plots as the reasons for not using methods like remote sensing. However, in developed countries, distributed agro-hydrological models have now been in full swing (Jiang et al., 2015; Singh, Kroes, van Dam, & Feddes, 2006; Xue & Ren, 2016). Some developing countries are not left out, as an example, Ahmad, Turral, & Nazeer(2009) used remote sensing to assess the performance of large irrigation systems in Pakistan.

Several authors (Boelens & Vos, 2012; Gain & Giupponi, 2015; Vilanova et al., 2015; Wichelns, 2014; Yadav, Singh, Shah, & Gamit, 2014; Zhou, Deng, Wu, Li, & Song, 2017) believed that assessment of water supply systems requires considering several socioeconomic and political factors, not only physical water supply (technical aspects) and demand. For example, supply-side factors such as poor governance and institutional issues are also causing an inefficient water use (Bai, Zhou, Zhao, & Yu, 2017; Qureshi, Grafton, Kirby, & Hanjra, 2011), especially in Nigeria due to corruption (Auriol & Blanc, 2009; Estache, Goicoechea, & Trujillo, 2009). In fact, it is stressed that basin hydrology is profoundly political in nature (Vincent, 2003), as are irrigation efficiency indicators and goals (Boelens & Vos, 2012). Extension services are very crucial in providing the necessary knowledge to farmers to adopt and implement viable solutions for efficient water use. Because of that, Levidow et al., (2014) blamed the current on-farm water-efficiency levels on lack of adequate means and incentives on the farmers' side to know crops' water use, actual irrigation applications, and crops' yield response to different water management practices. They stressed that continuous knowledge-exchange is necessary so that all relevant stakeholders can share greater responsibility across the entire water-supply chain. Hence, many research, such as, (European Comission, 2003; Ruiz-Villaverde & García-Rubio, 2017; Vilanova et al., 2015) concluded that performance measurement and indicators must be developed according to systems' characteristics, based on performance goals in a collaborative process involving stakeholders and technical actors.

Management of water supply systems is often influenced by the type of ownership and operation (public or private ownership and operation). Okeola & Sule (2012) evaluated these management alternatives using multi-criteria decision analysis, and stakeholders preferred public ownership and operation as the most sustainable operation of urban water supply delivery.

In light of these considerations, this thesis presents a literature review on performance evaluation and indicators applied to water supply systems. It aims to provide an overview and the advances in measurement and monitoring tools that may contribute to the efficiency, effectiveness, and sustainability of water supply utilities through analytical techniques.

2.2 Performance assessments in water resources management

In its broadest sense, performance assessment involves quantifying the efficiency of resources use and the effectiveness of processes linked to these actions (Bos et al., 1994; Neely, Gregory, & Platts, 2005). What efficiency means it is much debated until now (Birkenholtz, 2017; Boelens & Vos, 2012; Haie, 2008; Lankford, 2012; Luis Santos Pereira, Oweis, & Zairi, 2002; Perry, 2007, 2008, 2011). The complexity of water systems and the need to adapt them to changing conditions require developing approaches able to synthesize the system performance through specific parameters measured or evaluated by numerical simulations. These measurements allow a basis for comparing similar units to identify an area for improvements and provides a framework for monitoring progress.

2.3 Performance indicators (PIs) of water supply systems

According to ISO (2007), an indicator is a parameter or a value derived from a parameter, which provides information about a subject matter with a significance extending beyond that directly associated with a parameter value. Performance indicators are tools employed in measurement and quantification of various aspects of effectiveness and efficiency of actions (Nudurupati, Bititci, Kumar, & Chan, 2011). Alegre et al. (2006) cited in Vieira, Alegre, Rosa, & Lucas (2008) defined PIs as a quantitative measure of the effectiveness (extent to which the targeted objectives are achieved) and efficiency (extent to which resources of a water utility are utilized optimally to produce a service) of a specific aspect of the service delivered by a water supplier. Performance indicators are typically expressed as ratios between variables that may be commensurate (e.g. %) or non-commensurate (e.g. $\$/m^3$).

Rao (1993) summarized the various performance indicators proposed by different authors for measuring irrigation system performance and explained their uses. Kloezen & Garcés-Restrepo (1998) proposed a list of indicators related to the hydrological, agronomic, economic, financial and environmental performance of irrigation systems. Bos et al. (1994) classified performance indicators as; water supply performance (e.g. water conveyance efficiency), agricultural performance, and economic, social and environmental performance. The authors further presented a framework and a set of indicators specifically for managers of canal systems that can be used in assessing irrigation performance as well for long-term performance assessment including physical, economic and social sustainability. Bos (1997) recommended some indicators that cover water delivery, water use efficiency, maintenance, sustainability or irrigation, environmental aspects, socio-economics and management. These indicators could be used in irrigation and drainage performance assessment. Indicators are used to describe hydrological behaviour in complex irrigation schemes through few and understandable numbers (Bastiaanssen et al., 2001).

The set of indicators used is usually the same in different countries and systems, despite different nomenclatures and data availability (Vilanova et al., 2015). Since performance means different things to different people, however, one element of strategic management is choosing the appropriate set of performance indicators (Bos et al., 1994). Trawick (2001) suggests using indicators based on the logic of the system as seen from the standpoint of people using it. Kamwamba-Mtethiwa, Weatherhead, & Knox (2015) reviewed the performance of small-scale irrigation pumped systems. Results revealed that approaches used in performance studies have an implication on the results outcomes. For example, research reporting positive impacts tended used socio-economic based factors, whereas studies reporting mixed performance relied more on technically based indicators. The analysis highlighted the sensitivity of interpreting conclusions from different studies and the need to be cautious when comparing performance within and between different types of irrigation systems.

In the drinking water sector, performance assessment has been carried out in the areas of drinking water production, storage and distribution. According Vieira et al. (2008), performance indicators promoted by International Water Association (IWA) and the World Bank are the most relevant developed for water supply systems and wastewater supply, although others can be mentioned. Generally, most of the indicators apply to only agricultural systems, but only a few are for both agricultural and water supply systems.

Two major approaches to performance evaluation have been considered;

1. how well service is delivered
2. the outcomes of irrigation in terms of efficiency and productivity of resource use.

These have been referred to as internal and external performance, with internal or process indicators measuring one, and external or output indicators measuring the others. Recent work on performance assessments have used both these for assessing (Gomo et al., 2014; Usman, Liedl, & Awan, 2015) and benchmarking performance (Borgia, García-Bolaños, & Mateos, 2012; Córcoles, de Juan, Ortega, Tarjuelo, & Moreno, 2012). External performance indicators generally lend themselves better than internal indicators (i.e., those that describe internal irrigation processes of water distribution) to cross-scheme comparison because internal indicators are usually scheme-specific so data collection is time consuming, expensive, and complex (Molden, Sakthivadivel, Perry, De Fraiture, & Kloezen, 1998).

2.3.1 Agricultural performance indicators

This subsection introduces some essential discussions over agricultural water indicators as reported in literature.

2.3.1.1 Irrigation efficiency

Irrigation efficiency is a measure of the effectiveness of irrigation. It is a parameter which defines irrigation performance. The classical efficiency has been used throughout the world since the 1930s to design and operate irrigation systems until the present day (Haie & Keller, 2014). Israelsen (1932) defined irrigation efficiency as the ratio between crop water requirements (CRW) and the applied water. Later, authors improved and refined this original definition. A detailed discussion of history and various irrigation efficiency concepts was presented (Burton, & Molden, 2005; Bos & Nugteren, 1974; Burt et al., 1997; Jensen, 1966; Jensen, 2007; Keller, Keller, & Seckler, 1996; Pereira et al., 2002; Perry, 2007; Van Halsema & Vincent, 2012; Wichelns, 2002) and how this technical concept is sometimes lost in translation when applied at different spatial scales (Lopez-Gunn, Zorrilla, Prieto, & Llamas, 2012). Presently, several scholars have defined CE as the ratio of water volume beneficially used by plants to the volume of water delivered through an irrigation system, adjusted for effective rainfall and changes in the water storage in the root zone.

Mathematically;

$$\boldsymbol{CE = \frac{ET}{VA}} \qquad \textbf{(1)}$$

Where CE = classical efficiency; ET = net crop evapotranspiration; VA = diverted water

However, due to the complexity of WUSs and increasing competition among various water users, simple efficiency indicators have proven inadequate in promoting an efficient WUSs design and evaluation, hence the need for composite performance indicators. Consequently, multiple studies have proposed Effective Efficiency and Net Efficiency that incorporate the issues as mentioned above (Haie & Keller, 2008; Keller et al., 1996). Unfortunately, the terms are mostly used outside the context for which it was defined initially and at different levels. Given that, several authors, such as Van Halsema & Vincent (2012) investigated the use and misuse of terminologies and applications of irrigation efficiency concepts, water use efficiency and water productivity.

In order to avoid misconceptions, researchers have stressed the importance of efficiency terminology (Heydari, 2014; Pereira, 1999; Perry, Steduto, Allen, & Burt, 2009; Qureshi et al., 2011; Vilanova et al., 2015) and methodologies for calculating it using the law of conservation of mass (Frederiksen & Allen, 2011; Pereira et al., 2012). Besides, application of these concepts for evaluating irrigation systems and quantitative analysis of these indices were only made in few studies (Ahmad, Haie, Yen, & Tuqan, 2017; Ghahroodi et al., 2015; Haie & Keller, 2008; Lecina, Neale, Merkley, & Dos Santos, 2011). However, even when they are evaluated Van Halsema & Vincent (2012) pointed out that the data on actually measured efficiencies are hardly used in system operation.

Several authors noted the use of the term ‘efficiency’ often leads to misconceptions and misunderstandings, especially when the increasing efficiencies is equated with creating more available water (Birkenholtz, 2017; Boelens & Vos, 2012; Haie, 2016; Heydari, 2014; Jensen, 2007; Lankford, 2012; Perry, 2007), and when water quality issues are involved (Ayars & Schoneman, 2006; Haie & Keller, 2014; Qureshi et al., 2011), and socio-economic analysis ignored (Keller et al., 1996; Qureshi et al., 2011; Wichelns, 2002). Many authors who developed neoclassical definitions of efficiency have recognised the vital role of economic analysis. Scholars noted the limitation of IE as addressing to only physical quantities of water, both in its numerator and denominator, while ignoring the differences in the value of water in alternative uses. Keller et al. (1996) suggested that significant economic gains could be made by reallocating water from a lower value to higher valued crops even if a closed irrigation system is operating at close to 100% overall physical efficiency. Hence, the water productivity terms (WP) (Molden & Sakthivadivel, 1999) water footprint (Chapagain & Hoekstra, 2008). However, indicators of WP do not describe the extent of externalities that may be reducing the land and water productivity in a particular region and ignores many beneficial water flow paths and inputs, such as fertiliser, pesticides and type of soil, that contribute to better productivity, and therefore is flawed (Boelens & Vos, 2012; Haie, 2016; Wichelns, 2014, 2015a, 2015b). Re-allocation of water (rights) to gain productive efficiency may mean that some win and others lose access to water, in particular, the poor users (Boelens & Vos, 2012). It is employed because, on the surface, it seems compelling to consider maximising, for example, crop per drop. Or to suggest that more food must be produced with less water. This notion was popularised by former UN Secretary-General Kofi Annan’s proclamation that considering water scarcity and food insecurity; the global water community must find ways to achieve “more crop per drop” in irrigated agricultureMoreover, Boelens & Vos (2012) and Fereres et al. (2017) highlighted some important limitations of WF as an indicator of water use in food production and suggested alternative views regarding the assessment of water use in irrigated agriculture.

2.3.2 Municipal water supply performance indicators

Performance assessments of urban water supply have been carried out all over the world since the 1970s using different methods and models. The procedures employed are based on key performance indicators organised in a report or models applying mathematical methods that defined an overall performance indicator that synthesises a group of measures in a single score (Da Cruz, Marques, Romano, & Guerrini, 2012; Romano & Guerrini, 2011). The varieties of indicators should not be considered as a constraint but, instead, should provide the decision maker with a wide range of choices of relevant indicators and the possibility of adapting them according to context and needs. The selection of indicators remains a challenge for utilities, especially small ones (Nafi, Tcheng, & Beau, 2015).

Typically, performance indicators assess include; coverage of water supply connection, per capita supply of water, extent of metering of water connections, extent of non-revenue water, continuity of water supply, quality of water supplied, efficiency in redressal of customer complaints, cost recovery of water supply services and efficiency in collection of water supplied related charges.

Over the time several authors have proposed methods for evaluating performance of urban water supply using various indicators. To understand more on these indicators, (Haider, Sadiq, & Tesfamariam, 2014) summarised the various performance indicator systems proposed by the different organisation for measuring small- and medium-sized water supply system performance and explained their uses. The study concluded that the selection of suitable PIs depends on the type of the water source and quality. A conceptual performance evaluation system for small- and medium-sized water supply consisting of a list of PIs grouped into their respective categories was proposed.

Similarly, Abbott & Cohen (2009) reviewed different methods used to determine levels of productivity and efficiency in the water sector, highlighting the input and output data requirements of these methodologies, economies of scales, public versus private ownership and the impact of regulation. Many scholars have proposed performance assessment for water supply systems (Cardoso, Coelho, Matos, & Alegre, 2004; Kanakoudis, Tsitsifli, Samaras, Zouboulis, & Demetriou, 2011; Vieira et al., 2008). The performance areas explored for water supply are: hydraulics, water quality and reliability. The methodology was based on the application of performance functions to the values of particular variables at each pipe or node of the network.

Partial measures (single dimension indicators) are intuitive and easy to compute. However, if used to compare the performance of many firms, it can lead to some misinterpretations and do not allow for the definition of an overall performance ranking (R. C. Marques, 2008). Indeed, the weakness of these measures is the failure to cover all inputs, outputs and explanatory factors that are relevant to the performance of the decision-making units (Da Cruz et al., 2012).

2.4 Proposed and implemented approaches in performance assessment for agricultural and urban water supply systems

This subsection is aimed at understanding some available methods used in measuring performances of WUS, their frequencies of use, and their spatial applications worldwide. As discussed earlier, in response to the appealing situations over the terminology issues, alternative terms and indicators were proposed that would ensure acceptability and common usage. These approaches were based upon the water use fractions, factorials and water accounting where water balance is central to (basin) water allocation and its assessment. Beneficial and non-beneficial water uses were also integrated into some of the techniques.

Molden & Sakthivadivel (1999) proposed and demonstrated the use of water accounting using humid and arid region in Sri Lanka and Egypt, respectively, as case studies. Different authors employed water accounting methodology (Frederiksen & Allen, 2011; Gleick, Christian-Smith, & Cooley, 2011; Karimov, Molden, Khamzina, Platonov, & Ivanov, 2012; Lecina et al., 2011). In addition to using water accounting approach, some researchers have resorted to developing and employing an integrated approach with other methods as can be found in Lecina et al. (2011). Alternatively, other methods have inherently great limitations. (Hsiao, Steduto, & Fereres, 2007) proposed a framework based on the fact that the overall efficiency of any process consisting of a chain of sequential steps is the product of the efficiency (i.e. output/input ratio) of its individual component steps. However, Qureshi et al. (2011) argued that such approach can only yield limited guidance to underpin water policy decisions, especially when water quality and environmental implications are involved. This is because the method as the title suggested was based on quantitative approach. Other authors that developed techniques or models are summarized in Table 2 and Table 3 summarizes the findings of the state-of-the-art which can be found at the end of this section.

Several authors have combined techniques to assess the performance of irrigated areas through external indicators, such as efficiencies or productivities and analysed the internal irrigation processes related to timing, duration or water flows to diagnose performance (Abou Kheira, 2009; Causapé, Quílez, & Aragüés, 2006; Gorantiwar & Smout, 2005; Jayatillake, 2004; Sanaee-Jahromi & Feyen, 2001). In trying to come up with best management scenarios or alternatives for sustainable water management, scholars have come up with some interesting results that could have serious implications. Some of the results are contrary to the general discourse. For example, high complexity in technology changes would not necessarily create greater water performance or reducing water abstraction does not necessarily increase efficiency or downstream water availability, for example, changing (gravity) surface irrigation methods to drip or sprinkler systems (Ahmad, Masih, & Giordano, 2014; Haie, 2016; Molle & Tanouti, 2017).

Irrigation performance indicators have proved very useful in assessing water management at different spatial scales: field, farm, irrigation district and basin scale (Ghahroodi et al., 2015; Haie & Keller, 2012, 2014; Qureshi et al., 2011; Rowshon, Mojid, Amin, Azwan, & Yazid, 2014). Performance indicators have also used in a greenhouse horticultural production area (Sánchez, Reca, & Martínez, 2015a, 2015b).

Performance assessments have been done from different perspectives - of researchers, donors, farmers, irrigation managers and government. Many researchers have recommended developing participatory irrigation management because performance of irrigation schemes are multidimensional and can be looked at from different perspectives (Carr, Blöschl, & Loucks, 2012; K. Madhava Chandran & Ambili, 2016; Dejen et al., 2012; European Comission, 2003; Gomo et al., 2014; Kono, Ounvichit, Ishii, & Satoh, 2012; Kuscu, Eren, & Demir, 2009; Uysal & Atiş, 2010). Performance assessment can be useful to managers if they participate in the process (Douthwaite et al., 2009). Here, one of the managers are farmers who individually manage their plots and collectively manage their irrigation schemes. Ray, Dadhwal, & Navalgund (2002) reported that a system that is considered fair by most farmers is more efficient than the one that the water authority has designed on the basis of productivity and efficiency but which is considered unfair by the farmers. Additionally, farmers are better placed than anyone else to carry out monitoring, especially at the farm level (Dembele et al., 2012). A comprehensive review on evaluating participation in water resources management was provided by Carr et al. (2012). For sustainable agricultural development, there is a need to develop management policies with an integration of stakeholders' participation so that the outcome will suit the local hydro-climatic environment and the socio-economic conditions (Alordzinu, Sam-Amoah, & Owusu-Sekyere, 2017; K. Madhava Chandran & Ambili, 2016; Dembele et al., 2012; Matekere & Lema, 2011; Njiraini & Guthiga, 2013).

Traditionally, field experiments are conducted to quantify and evaluate water management practices in irrigation systems (Andrés & Cuchí, 2014; Dejen et al., 2012; Gomo et al., 2014a; Mondal & Saleh, 2003; Singh et al., 2006), even though they are often expensive and time-consuming (Sam-Amoah & Gowing, 2001). Some field observations of irrigation events were conducted to obtain data for characterizing the water management in many irrigation schemes, especially in developing countries. Refer to Table 3. However, specific recommendations derived from site-specific field experiments cannot be generalised to regional level with different ecohydrological conditions, hence other methods like remote sensing.

Remote sensing is a new and more encompassing technology that offers an accurate and profound understanding that cannot be obtained from conventional field measurement (Bastiaanssen & Bos, 1999; Perry, 2005). Remote sensing allows securing near-real-time spatial crop data regarding the type of crop, crop growth and development, water status, and even biomass and crop yield uniformity at the plot and subplot levels. Recent studies has indicated that GIS/remote sensing is a reliable technique and is fast gaining ground in performance assessment studies (Ahadi, Samani, & Skaggs, 2013; Ahmad et al., 2009; Akbari, Toomanian, Droogers, Bastiaanssen, & Gieske, 2007; Bastiaanssen et al., 2001; Karatas, Akkuzu, Unal, Asik, & Avci, 2009; Karimi, Bastiaanssen, & Molden, 2013; Karimi, Bastiaanssen, Molden, & Cheema, 2013; Rowshon, Amin, & Shariff, 2011; Singh et al., 2006; Usman et al., 2015). Except in a few countries in Africa (Ahmed, Tanakamaru, & Tada, 2010; Al Zayed, Elagib, Ribbe, & Heinrich, 2016; Borgia et al., 2012; Hamid et al., 2011; Hellegers, Soppe, Perry, & Bastiaanssen, 2010; Kharrou et al., 2013; Zwart & Leclert, 2010), there are hardly any studies that employed remote sensing for assessing irrigation managemet. This is probably due to the nature of the hardware and software used in that kind of research which are often expensive.

In many countries today, irrigation systems management has been transferred to water user associations (WUAs). The belief is that performance of irrigation systems is dependent on the performance of the WUAs (Uysal & Atiş, 2010), which could be evaluated by performance indicators. Thus, spatiotemporal patterns of indicators could give information on the functioning of the WUAs and allow different irrigation systems to be compared. Several researchers have shown differences between different types of WUAs around the world using performance indicator comparisons (Awan, Tischbein, Conrad, Martius, & Hafeez, 2011; Chandran & Ambili, 2016; Córcoles et al., 2012; Córcoles, de Juan, Ortega, Tarjuelo, & Moreno, 2010; Karatas et al., 2009; Kazbekov, Abdullaev, Manthrithilake, Qureshi, & Jumaboev, 2009; Uysal & Atiş, 2010).

Performance indicators facilitate assessing irrigation schemes before and after rehabilitation or intervention, and in analysing scenarios (Angella et al., 2016; Barros, Isidoro, & Aragüés, 2011; García-Garizábal, Causapé, & Abrahao, 2011; Mateos et al., 2010; Merchán, Causapé, Abrahão, & García-Garizábal, 2015; Van Halsema, Lencha, Assefa, Hengsdijk, & Wesseler, 2011; Vandersypen et al., 2006; Yilmaz & Harmancioglu, 2012).

In recent decades many authors have developed and applied irrigation performance indicators and benchmarking techniques to identify the best irrigation practices and to compare different and complex irrigation systems (Borgia et al., 2013; García-Bolaños et al., 2011; Kifle, Gebremicael, Girmay, & Gebremedihin, 2017; Poussin et al., 2015). Furthermore, an economic approach rather than an engineering approach was used to defined and measured water use efficiency based on the concept of input specific technical efficiency (Bai et al., 2017; Gadanakis, Bennett, Park, & Areal, 2015; Kuppannan, Coimbatore Ramarao, Samiappan, & Malik, 2017; Lorite, García-Vila, Carmona, Santos, & Soriano, 2012; Olubode-Awosola, Idowu, & Van Schalkwyk, 2006; Pereira & Marques, 2017; Romano & Guerrini, 2011; Yigezu et al., 2013).

In the case of municipal water supply, many authors proposed and/or used performance indicators that express the level of service of a water system subjected to varying operating conditions over time (Asefa et al., 2014; Ashofteh, Rajaee, & Golfam, 2017; Cardoso et al., 2004; Chu, Wang, & Wang, 2015; Da Cruz et al., 2012; de Witte & Marques, 2010; Ermini et al., 2015; Mande Buafua, 2015; Marques, 2008; Mutikanga, Sharma, Vairavamoorthy, & Cabrera., 2010; Nafi et al., 2015; Romano & Guerrini, 2011; Sadiq, Rodríguez, & Tesfamariam, 2010; Vieira et al., 2008). Table 2 and 3 summarize the proposed and implemented approaches to performance assessment, respectively.

Table 2 Proposed performance indicators by various authors

No.	**Reference**	**Proposed model**	**Performance evaluation**		
			A	**U**	**AU**
1.	Bai et al. (2017)	NMWUPI method			■
2.	Bos et al. (1994)		■		
3.	Carden & Armitage (2013)	SIUWM		■	
4.	Cardoso et al. (2004)	PAS		■	
5.	Ermini et al. (2015)				■
6.	Frederiksen & Allen (2011)	WUA			■
7.	Ghahroodi et al. (2015)		■		
8.	Gorantiwar & Smout (2005)		■		
9.	Haie & Keller (2012)	Sefficiency			■
10.	Hashimoto et al. (1982)	RRV		■	
11.	Karimi, Bastiaanssen, & Molden (2013)	WA+	■		
12.	Nafi et al. (2015)	Overall indicator		■	
13.	Pereira et al. (2012)	Consumptive & beneficial use			■
14.	Sanaee-Jahromi & Feyen (2001)		■		
15.	Vieira et al. (2008)			■	

Note: A = agricultural, U = urban, B = both agricultural and urban

Table 3 Performance assessment studies: category, location, methodology, indicators used and major findings

No.	Reference	WUS			Location/Methodology	Indicators evaluated	Major findings
		A	U	AU			
1.	Ahadi et al. (2013)	■			Location: Mexico Techniques: remote sensing, ground level measurements	on-farm irrigation efficiency, district efficiency	approach capable of determining the inefficiency of the system
2.	Ahmad et al. (2009)	■			Location: Pakistan Techniques: remote sensing	equity, adequacy, reliability, water productivity,	approach provide better estimates of irrigation performance at a variety of scales
3.	Ahmad et al. (2014)	■			Location: Pakistan Techniques: physical measurement, farmer survey	water productivity	technologies do not necessarily may not reduce water use unless institutional arrangements
4.	Ahmad et al. (2017)	■			Location: Nigeria Techniques: Sefficiency	classical efficiency, meso-level Sefficiency	management perspective is more holistic than farmers' – underscore stakeholders participation
5.	Ahmed et al. (2010)	■			Location: Sudan Techniques: remote sensing, field data	crop water requirements, yield, water productivity	close linear relationship between yield and water productivity
6.	Akbari et al. (2007)	■			Location: Iran Technique: remote sensing	relative water supply, water productivity, biomass growth rate	approach has advantages over traditional assessments
7.	Akkuzu, Unal, Karatas, Avcı, & Asık (2007)	■			Location: Turkey Techniques: physical measurements	level of realisation of irrigation ratios, level of realisation of crop pattern, dependability, adequacy, efficiency, equity	highlights the relationship between dependability, equity, adequacy and efficiency. Important of stakeholder participation
8.	Al Zayed & Elagib, (2017)	■			Location: Sudan Techniques: remote sensing	crop water consumption index	approach is useful in schemes where validation data are extremely difficult to obtain

No.	Reference	WUS			Location/Methodology	Indicators evaluated	Major findings
		A	U	AU			
9.	Al Zayed, Elagib, Ribbe, & Heinrich, (2015)	■			Location: Sudan Techniques: remote sensing	relative water supply, relative irrigation supply	low productivity is mainly due to poor distribution and irrigation mismanagement
10.	Alordzinu et al., (2017)	■			Location: Ghana Techniques: field measurements and data	conveyance efficiency, dependability of irrigation intervals, relative rrigation supply, output per unit irrigation supply, water productivity per unit crop evapotranspiration	highlights the importance of active participation of farmers as major stakeholders
11.	Andrés & Cuchí, (2014)	■			Location: Spain Techniques: field data, water balance	irrigation efficiency, irrigation drainage fraction, water deficit, relative irrigation supply, water productivity	indicators provided an opportunity to analyse large and mature sprinkler irrigation district
12.	Angella et al., (2016)	■			Location: Argentina Techniques: field survey, AquaGIS	yield, harvest index, ratio of actual transpiration to the maximum transpiration that could be achieved in the simulation without stomatal closure, irrigation, drainage, relative drainage index, water productivity, irrigation water productivity	potential of combining field data with AquaCrop to quantify the yield and water productivity gaps to propose management recommendations for closing the gaps
13.	Asefa et al., (2014)		■		Location: USA Techniques: Reliability, Resilience and Vulnerability, Monte-Carlo	reliability, resilience and vulnerability	method was a novel approach to quantifying water resources system vulnerability

No.	Reference	WUS			Location/Methodology	Indicators evaluated	Major findings
		A	U	AU			
14.	Ashofteh et al., (2017)			■	Location: Iran Methodology: WEAP	reliability, vulnerability, resiliency, flexibility	efficiency indicators are effective tools of analysing reservoir behavior, especially determination of critical period in operating interval
15.	Awan et al., (2011)	■			Location: Uzbekistan Techniques: remote sensing (SEBAL), hydrological field measurements	relative evapotranspiration, delivery performance ratio, drainage ratio, depleted fraction, overall consumed ratio, field application ratio, conveyance ratio	delivery performance ratio, relative evapotranspiration and drainage ratio show inadequacy, inequity and unreliability at irrigation system, and overall consumed ratio and depleted fraction show the inefficiency at system levels
16.	Bai et al., (2017)		■		Location: China Techniques: non-radial Malmquist water use performance index	water use efficiency	technological improvement and institutional construction are critical in urban water management especially in developing countries
17.	Barros et al., (2011)	■			Location: Spain Techniques: field data	relative water deficit, irrigation consumptive use coefficient, drainage fraction	better irrigation management is achievable by implementing particular measures
18.	Bastiaanssen et al., (2001)	■			Location: Brazil Techniques: remote sensing, field data	relative water supply, overall consumed ratio, depleted fraction, crop water deficit, relative evapotranspiration, relative soil wetness, biomass yield over irrigation supply	approach provides opportunities to retrieve new performance indicators. However, it only measures net effects, expensive, and provides a regional scale overview and low resolutions images

No.	**Reference**	**WUS**			**Location/Methodology**	**Indicators evaluated**	**Major findings**
		A	**U**	**AU**			
19.	Borgia et al., (2012)	■			Location: Mauritania Techniques: field observations and satellite images	irrigation adequacy, drainage adequacy	variability in irrigation supplies and drainage ere main sources of variability of yields and irrigation intensity, and physical, technical, and organisational factors underlie non-uniform water distribution patterns
20.	Borgia et al., (2013)	■			Location: Mauritania Techniques: Cluster and data envelopment analyses	adequacy, energy cost, relative irrigation supply, irrigation intensity, land productivity	comparative performance assessment based solely on indicators might be challenging to interpret as the result may vary significantly depending on the indicators used
21.	Buafua (2015)		■		Location: Sub-Saharan Africa Techniques: SFA, translog production frontier	inputs: Water distribution mains length, Total number of personnel, Volume of water lost output: Volume of water delivered	private-sector participation in management has a positive effect on technical efficiency.
22.	Causapé et al., (2006)	■			Location: Spain Techniques: Review	irrigation efficiency	the short duration of most surveys and lack of standards for conducting irrigation efficiency and mass balance studies at the irrigation district level as the most important constraints limiting this kind of studies
23.	Chandran & Ambili, (2016)	■			Location: India Techniques: field survey, physical measurement	relative water supply, relative irrigation supply, standardized	participatory farmer activities in management/distribution for better water management are evident

No.	Reference	WUS			Location/Methodology	Indicators evaluated	Major findings
		A	U	AU			
		■				gross value of production (SGVP), SGVP per cropped area, SGVP per unit irrigation supply	
24.	Chandran, Joseph, & Sushanth (2016)	■			Location: India Techniques: field survey	adequacy, timeliness, equity, accountability, adequate and timely repair and maintenance of infrastructure	trust farmers have for their own institution (i.e. WUA) for water management
25.	Chu et al. (2015)		■		Location: China Methodology: Cluster analysis technique	13 indicators	proposed indexes and its application can help provide quantitative information on the urban water cycle performance status
26.	Cardoso et al. (2004)		■		Location: Portugal Techniques: Performance assessment system	water level, flow velocity	approach highlights the main strengths and weaknesses, and is well suited to time- or scenario-oriented comparative analyses
27.	Clemmens & Molden (2007)	■			Location: Projects around the world Techniques: rapid appraisal process (RAP)	relative irrigation water supply, relative water supply\	
28.	Córcoles et al. (2010)	■			Location: Spain Techniques: benchmarking	total annual volume of irrigation water supply, total annual volume of irrigation water delivery, total annual volume of water supply, annual irrigation water supply per unit command area, annual irrigation water supply per unit irrigated area, main system water	annual irrigation water supply per unit irrigated area is a useful indicator in explaining the key features of WUAs. CEN per unit irrigated area and per unit irrigation delivery are significant in describing the characteristics and differences between WUAs

No.	Reference	WUS			Location/Methodology	Indicators evaluated	Major findings
		A	U	AU			
		■				delivery efficiency, annual relative water supply, annual relative irrigation water supply, water delivery capacity	
29.	Córcoles et al. (2012)	■			Location: Spain Techniques: benchmarking	???	water applied in most of the plots in drip irrigation systems is slightly higher than crop water requirements
30.	Da Cruz et al. (2012)		■		Location: Portugal, Italy Techniques: data envelopment analysis	revenue water volume, Population served	Italian is more efficient than Portuguese utilities with VRS model, and vice versa with CRS model
31.	de Witte & Marques (2010)		■		Location: Netherlands, England and Wales, Portugal, Belgium, Australia Techniques: data envelopment analysis	input: number of employees, length of mains Output: water delivery number of connections	revealed substantial differences in bias and noise corrected first stage inefficiencies
32.	Dembele et al. (2012)	■			Location: Burkina Faso Techniques: field data, surveys	production and productivity, profitability, resource use, organizational viability	method suitable for large-scale irrigation systems and indicators involving water measurements are more difficult to calculate
33.	Dejen et al. (2012)	■			Location: Ethiopia Techniques: field survey, GIS-based	annual relative water supply, annual relative irrigation supply, output per unit irrigation water diverted/supplied, output per unit irrigation water delivered to the command, output per unit water diverted/supplied and output per unit water consumed	indicators are useful for cross-comparison in irrigation schemes.

No.	Reference	WUS			Location/Methodology	Indicators evaluated	Major findings
		A	U	AU			
34.	Fernández García, Rodríguez Díaz, Camacho Poyato, Montesinos, & Berbel (2014)	■			Location: Spain Techniques: field data	15 indicators	reduction in water diverted for irrigation, with a hike in water costs due to energy consumption, and farmers were migrating to more profitable crops with higher water requirements
35.	Gadanakis et al. (2015)	■			Location: England Techniques: benchmarking, data envelopment analysis	technical efficiency, water use efficiency	recycling water and practising a particular irrigation system has a positive impact on water use efficiency at a farm level, whereas the use of other irrigation systems affect water use efficiency
36.	García-Bolaños et al. (2011)	■			Location: Mauritania Techniques: field survey, physical measurements	irrigation intensity, water delivery capacity, relative irrigation supply, water productivity, fuel productivity, equity, reliability, flexibility, adequacy, efficiency	disparities among schemes were so significant that differences between performance indicators in rehabilitated and non-rehabilitated schemes were not statistically significant
37.	García-Garizábal et al. (2011)	■			Location: Spain Techniques Irrigation Land Environmental Evaluation Tool	net hydric needs, irrigation, efficiency, water deficit	approrach assess irrigation management alternatives and the effect of multi-annual climatic and agronomic variables
38.	Ghahroodi et al. (2015)	■			Location: Iran Techniques: physical measurements, field data	classical efficiency, effective efficiency, water productivity	effective efficiency represents irrigation systems performance at farm scale more correctly, and combined application of the concepts is suitable for improving irrigation water management

No.	Reference	WUS			Location/Methodology	Indicators evaluated	Major findings
		A	U	AU			
39.	Gomo et al. (2014)	■			Location: South Africa Techniques: Field survey, AHP	conveyance efficiency, dependability of interval between water applications, relative irrigation supply, output per unit irrigation supply, output per unit water consumed	such indicators are capable of assessing smallholder irrigation schemes
40.	Haie (2016)	■			Location: -Ananymous Techniques: Sefficiency	micro, meso and macro Sefficiency	technology changes would not necessarily create greater water performance and reducing water abstraction does not necessarily increase efficiency or downstream water availability
41.	Haie & Keller (2012)			■	Location: Nile, Grand Valley, City 1 2020 and hypothetical case Techniques: Sefficiency	micro, meso and macro Sefficiency	method shows tendency of flawed interpretations in decision making
42.	Hamid et al. (2011)	■			Location: Sudan Techniques: remote sensing (SEBAL)	adequacy, equity, dependability, water use efficiency	methodology employed could be considered a complementary tool to guide irrigation water management decisions in large-scale irrigation systems. only high-resolution images could be used at farm plot size which is costly as compared to a coarse spatial resolution used for large units
43.	Hellegers et al. (2010)	■			Location: South Africa Techniques: remote sensing	crop water productivity, economic water productivity	remote sensing combining with economic analysis allows comparison of the opportunity costs

No.	Reference	WUS			Location/Methodology	Indicators evaluated	Major findings
		A	U	AU			
		■					of allocating water in a socially desirable way
44.	Ishii & Katsumata (2007)		■		Location: Japan Techniques: hypothetical examples	leakage ratio, water charge, pipeline burst ratio, redundancy	performance indicators made an evaluation of new project easy
45.	Jayatillake (2004)	■			Location: Sri Lanka Techniques: Benchmarking	cropping intensity, length of irrigation season, irrigation duty, water duty	compare regional variation in performance and among different types of schemes such as reservoir-backed schemes and diversion schemes, change of performance in various climatic zones
46.	Jiang et al. (2015)	■			Location: China Techniques: SWAP-EPIC, ArcInfo GIS	irrigation efficiency, water productivity	Field experiments have been extensively used to evaluate water management practices but are often expensive, time-consuming and site-specific
47.	Karatas et al. (2009)	■			Location: Turkey Techniques: remote sensing	overall consumed ratio, relative water supply, depleted fraction, crop water deficit, relative evapotranspiration	remote sensing provides opportunities to retrieve new performance indicators
48.	Karimi, Bastiaanssen, Molden, et al. (2013)	■			Location: Indus basin (Pakistan, India, China, and Afghanistan Techniques: remote sensing	water productivity	opportunities for reducing water depletion is through decreasing wasteful soil evaporation in agricultural areas
49.	Kazbekov et al. (2009)	■			Location: Kyrgyzstan Techniques: field survey	adequacy, efficiency, dependability, equity	viable and simple performance assessment tools are a pre-requisite for the development of operational WUAs universally

No.	Reference	WUS			Location/Methodology	Indicators evaluated	Major findings
		A	U	AU			
50.	Kharrou et al. (2013)	■			Location: Morocco Techniques: remote sensing	relative irrigation supply, depleted fraction, relative evapotranspiration, coefficient of variation of ET_c	remote sensing-based estimates of water consumption could provide a more desirable picture of irrigation performance at different scales than field survey methods
51.	Abou Kheira (2009)	■			Location: Egypt Techniques: field survey	water use index, operating cost per unit volume of water, total cost per unit of water, irrigation time per unit of area, incidence of night irrigation, land saving ratio.	converting the pumping unit from diesel engines to operate by electric engines will achieve many benefits in agricultural water management at the small-scale level and in regards to the cost of the irrigation operation
52.	Kifle et al. (2017)	■			Location: Ethiopia Techniques: experimental and physical measurements, statistical analysis	application efficiency, distribution uniformity, deep percolation loss , tail water runoff loss, irrigation water use efficiency	irrigation flow methods were significantly affected by the irrigation performance indicators
53.	Kono et al. (2012)			■	Location: Japan Techniques: Descriptive	participatory irrigation management	participation of farmers in the decision process at all levels is fundemental to realization of goals
54.	Kuppannan et al. (2017)	■			Location: India Techniques: field survey, empirical model	irrigation efficiency, water productivity	simultaneous consideration of two measures is essential to derive essential interventions for improving individual input use efficiency
55.	Kuscu et al. (2009)	■			Location: Turkey Techniques: field data	rate of irrigation, relative water supply, effectiveness of fee collection, financial self-	performance measurement systems should be designed to take into both physical, financial and social performance indicators in a

No.	Reference	WUS			Location/Methodology	Indicators evaluated	Major findings
		A	U	AU			
		■				sufficiency, staffing number per unit area	balanced and integrative perspective
56.	Lecina, Isidoro, Playán, & Aragüés (2010)	■			Location: Spain Techniques: water accounting	water accounting	water availability is reduced due to irrigation modernization, even though there is increase in on-farm irrigation efficiency. water accounting should be applied instead of the irrigation efficiency.
57.	Lecina et al. (2011)	■			Location: USA Techniques: Ador-Simulation	irrigation efficiency, water accounting	water accounting overcomes the limitations and hydrological misunderstandings of traditional analysis based on irrigation efficiency
58.	Lorite et al. (2012)	■			Location: Spain Techniques: field survey, water-balance simulation model	annual relative irrigation supply, crop yield ratio, irrigation water productivity, irrigation water benefit	agronomic indicators revealed most farmers did not adhere to recommendations and economic indicators did not only facilitate obtaining more satisfactory and economically viable irrigation scheduling but also brings about a greater acceptance of advisory services by farmers
59.	Marques & Monteiro (2001)		■		Location: Portugal Techniques:	50 indicators	indicators were associated with a hierarchical structure of knowledge or development according to different levels: basic level,

No.	Reference	WUS			Location/Methodology	Indicators evaluated	Major findings
		A	U	AU			
			■				development level and strategic level
60.	Marques (2008)		■		Location: Portugal Techniques: performance indicators, total factor productivity, data envelopment analysis	performance indicators	performance of private management in Portugal exceed that of the public ones, in terms of water quality and productivity. However, the results suggested an opposite trend as far as efficiency is concerned.
61.	Matekere & Lema (2011)	■			Location: Tanzania Techniques: field survey	Construction time and cost, Irrigation efficiency	performance indicators currently used in Tanzania, which included traditional time and cost indicators, are not significant in improving performance
62.	Mateos et al. (2010)	■			Location: Mauritania Techniques: case study application, network distribution model and field water balance	water delivery capacity, relative irrigation supply, adequacy, reliability	indicators effectively analysed different elements and farmers' perception of the system performance. before rehabilitation the scheme could operate satisfactorily if proper maintenance were practised and after rehabilitation, more land is required which leads to increase in crop water requirements
63.	Merchán et al. (2015)	■			Location: Spain Techniques: field survey, EMR 2.0 (Irrigation Land Environmental Tool)	net hydric needs, irrigation efficiency, irrigation drainage fraction, water deficit	improvement in irrigation management is vital for a continued increase in irrigation efficiency

No.	Reference	WUS			Location/Methodology	Indicators evaluated	Major findings
		A	U	AU			
		■					while decreasing evaporation and wind drift losses, drainage fraction, and water deficit
64.	Mondal & Saleh (2003)	■			Location: Bangladesh Techniques: field measurements and questionnaire survey	delivery performance ratio, water delivery performance, conveyance loss ratio, relative water supply, overall reliability, equity, irrigated area ratio, yield ratio, production ratio, total financial viability, fee collection performance, profitability of farmers, sustainability of irrigated area	hydraulic, agricultural and socio-economic indicators used were recommended for evaluation of performances of irrigation projects and also for comparative analysis of performances of similar irrigation projects
65.	Moreno-Pérez & Roldán-Cañas (2013)	■			Location: Spain Techniques: GIS	relative irrigation supply, relative water supply, relative rainfall supply	relative irrigation supply is the most important indicator as it permits farmers' actual irrigation management practices to be determined and interpreted. using GIS to characterise irrigator communities and the inclusion of data on agronomic and hydraulic variables could significantly improve water management efficiency
66.	Mutikanga et al. (2010)		■		Location: Uganda Techniques:	19 indicators	PIs currently used are often not applicable in developing countries. developed computational tool will promote use of the standard water balance methodology for better

No.	Reference	WUS			Location/Methodology	Indicators evaluated	Major findings
		A	U	AU			
			■				assessment of water losses in utilities of developing countries
67.	Nafi et al. (2015)		■		Location: France Techniques: Overall indicator	26 indicators	performance assessment must go beyond technical boundaries and has to involve all aspects that could deteriorate the level of service
68.	Njiraini & Guthiga (2013)	■			Location: Kenya Techniques: DEA, field surveys	technical efficiency, water use efficiency	farmers realized 63 % technical efficiency and 31 % water use efficiency. enlightening farmers on the proper selection of crop combinations farmers and use appropriate irrigation techniques and attainment of acceptable levels of farm fragmentation is paramount
69.	Olubode-Awosola et al. (2006)	■			Location: Nigeria Techniques: field survey, analytical techniques	fee collection index, user's stake index, relative water cost and profit index, relative irrigation profit index financial self-sufficiency index	project was not financially viable and the farmers did not show commitment to making the project successful
70.	Pereira et al. (2012)	■			Location: Tunisia, Portugal, China, Uzbekistan Techniques: case study application	consumptive and beneficial use, water productivity	demonstrated the uncertainties in applying terms between and within water resources management and other groups of users, and it's consequence on poor use of water
71.	Poussin et al. (2015)	■			Location: Burkina Faso, Ghana Techniques: field survey	agronomic performance, economic performance	agronomic and economic performance were found to be less satisfactory in both schemes due to

No.	Reference	WUS			Location/Methodology	Indicators evaluated	Major findings
		A	U	AU			
		■					lack of maintenance of the reservoirs and irrigation schemes, sub-optimal crop management, and poor product marketing
72.	Ray et al. (2002)	■			Location: India Techniques: remote sensing, field data	adequacy (relative water supply), equity, water use efficiency	remote sensing-based performance indicators could identify the problem distributaries in the scheme, intensively managed and studied irrigation system. remote sensed data and GIS tools to calculate performance indices regularly could facilitate efficient irrigation system management
73.	Romano & Guerrini (2011)		■		Location: Italy Techniques: Data Envelopment Analysis		performance of water utilities was found to be subjective to ownership structure, size and geographical location, although with varying degrees of significance
74.	Rowshon et al. (2011)	■			Location: Malaysia Techniques: GIS-based	rice relative water supply, cumulative rice relative water supply, ponding water index	utility of integrating spatial and temporal information could evaluate the daily irrigation delivery performances (uniformity of water distribution and the shortfall or excess) using some water management scenarios
75.	Rowshon et al. (2014)	■			Location: Malaysia Techniques: field data	relative water supply, adequacy, equity, dependability	model is capable of assessing (quantitative assessment) not only water allocation for irrigation but

No.	Reference	WUS			Location/Methodology	Indicators evaluated	Major findings
		A	U	AU			
		■					also for day-to-day or periodic irrigation delivery performances
76.	Sadiq et al. (2010)		■		Location: Canada Techniques: ordered weighted averaging operator, field survey	source water, treatment, infrastructure, operational, maintenance	it is possible to combine information on operational, infrastructure, and maintenance characteristics to establish utility performance
77.	Sánchez et al. (2015a)	■			Location: Spain Techniques: statistical analysis	relative irrigation supply, annual relative water supply	RIS indicated that irrigation water exceeded net irrigation needs and high ARIS variability observed was confirmed to be as a result of the farmer management decisions
78.	Sánchez et al. (2015b)	■			Location: Spain Techniques: statistical analysis	crop water productivity, economic water productivity, productivity index, relative irrigation supply	the most significant variable affecting the productivity indices was the relative irrigation supply
79.	Sanaee-Jahromi & Feyen (2001)	■			Location: Iran Techniques: physical measurements, analytical method (Matrix D)	adequacy, reliability, equity	besides spatial and temporal variability, uniformity of the variability is also needed to assess the water delivery system
80.	Santos, Lorite, Tasumi, Allen, & Fereres (2010)	■			Location: Spain Techniques: remote sensing, water balance model	annual relative irrigation supply, irrigation water productivity	combining METRIC method in estimating actual ET with a water balance model allowed the determination of performance indicators reliably and accurately, requiring only very little data at the field level.

No.	Reference	WUS			Location/Methodology	Indicators evaluated	Major findings
		A	U	AU			
81.	Singh, Kroes, van Dam, & Feddes (2006)	■			Location: India Techniques: remote sensing, SWAP, field data	water productivity, net groundwater recharge and salt build-up	distributed ecohydrological modelling can provide a useful tool to evaluate the performance of irrigation systems at different spatial and temporal scales
82.	Setegn, Chowdary, Mal, Yohannes, & Kono (2011)	■			Location: Ethiopia Techniques: remote sensing, GIS	relative water supply, relative irrigation supply, depleted fraction, overall consumed ratio	suitable water management strategy by involving all stakeholders can guarantee the proper use of scarce water resources and improve the water application efficiency of the small-scale irrigation practices
83.	Unal, Asik, Avci, Yasar, & Akkuzu (2004)	■			Location: Turkey Techniques: field survey, physical measurements (Electronic limnigraphs)	adequacy, efficiency, dependability, equity	indicators were shown to have contributed to efficient water delivery monitoring and could identify the problems causing the poor performance of the system
84.	Usman et al. (2015)	■			Location: Pakistan Techniques: remote sensing, statistical analysis	equity, adequacy, reliability	spatially based analysis was performed at irrigation subdivisions, while temporal scales covered months, seasons and years. SEBAL results are comparable with advection aridity methods
85.	Uysal & Atiş (2010)	■			Location: Turkey Techniques: field survey, statistical analysis	relative water supply, cropping intensity, output per unit cropped area, output per unit irrigation supply, sustainability of irrigated area, area/infrastructure ratio, fee	utility, productivity, sustainability and financial efficiency was found to be positive and negative for adequacy. improved control and farmer education for a superior performance of all indicators, and

No.	Reference	WUS			Location/Methodology	Indicators evaluated	Major findings
		A	U	AU			
		■				collection performance, farmers' satisfaction	enhanced farmer participation in management should be achieved to raise the level of farmer satisfaction
86.	Van Halsema et al. (2011)	■			Location: Ethiopia Techniques: field mesurements and surveys	irrigation efficiency, relative irrigation supply	irrigation efficiency is 35%, but conveyance losses and application efficiencies differ extensively over the scheme. policy should concentrate on upgrading existing schemes rather than developing new ones
87.	Vandersypen et al. (2006)	■			Location: Mali Techniques: field survey, physical measurements, statistical analysis	adequacy, efficiency, dependability, equity	indicators appeared less relevant given that water supply is adequate. alternative procedure was proposed for conditions where water is sufficient. results of the adapted indicators revealed acceptable levels of dependability and equity
88.	Yigezu et al. (2013)	■			Location: Syria Techniques: stochastic production frontier and inefficiency model	technical efficiency, irrigation water technical efficiency, irrigation water technical cost efficiency	the current level of yield could be achieved with less irrigation water only by replacing surface canal irrigation with sprinklers. however, the shift produced only 2% improvement in a measure that combines both cost and technical efficiencies of irrigation water
89.	Yilmaz & Harmancioglu (2010)	■			Location: Turkey Techniques: WEAP	agricultural sustainability index, environmental sustainability index, water exploitation rate, yield	indicators verified that efficient water management is crucial to ensure the sustainable use of water

No.	Reference	WUS			Location/Methodology	Indicators evaluated	Major findings
		A	**U**	**AU**			
		■				reliability, irrigation water deficit, domestic supply reliability, benefit/cost ratio, irrigation water use efficiency, total production value	resources with respect to environmental, social and economic dimensions
90.	Zhou et al. (2017)	■			Location: China Techniques: field survey, stochastic frontier analysis	technical efficiency, irrigation water use efficiency	impact of PIM on IWUE is relatively small. water price, source of irrigation water, irrigation technology adoption and famers' education level and farming experience have significant positive impacts on IWUE
91.	Zwart & Leclert (2010)	■			Location: Mali Techniques: remote sensing, statistical analysis	cropping intensity, water productivity, uniformity, head–tail performance indicator	diagnostic performance assessment identifies needs for rehabilitation, whereas a comparative performance evaluation could set a benchmark, detect processes that could lead to higher performance and quantify the impact of an intervention

Note: A = agricultural, U = urban, AU = agricultural and urban

2.5 Water (re)allocation policies

Reallocation of water in an irrigation scheme is only possible by a detailed assessment of current performance (Usman et al., 2015), and linking water allocation and performance to productivity is very useful for policymakers (Ahmad et al., 2009; Chandran et al., 2016). There are other indicators used in (re)allocating water, Karimov et al. (2012) used water accounting procedure to determine a strategy that brought benefits by reallocating surplus winter flow from the upstream for summer use in the downstream.

However, water (re)allocation policies may be affected by the concepts of efficiency and productivity. In many national and international water policy documents, e.g., (DWR, 2012; European Commission, 2011; UK Defra, 2011; World Bank, 2017; World Water Assessment Programme (WWAP), 2012), efficiency and productivity concepts are used to transform water sector. In many countries, official water allocation is based on both the idea of optimising irrigation efficiency and water productivity. For instance, in Peru importance is attached to efficiency so much that an authority is responsible for issuing ‘efficiency certificates’ to efficient users and operators. These certificates give priority for obtaining new water rights (Boelens & Vos, 2012). The implication is communities, and other economically less powerful groups who have less access to ‘modern’ technology will be deprived of water. Forthermore, pproductivity of water can be dramatically different between uses. The value of water for municipal and industrial purposes is much higher than that for agriculture. An option for increasing productivity of water is to reallocate water from lower to higher value uses. As a result, downstream commitments may change, and any reallocation of water is likely to have legal, equity and other social considerations that must be addressed (Molden & Sakthivadivel, 1999). Hence, empirical estimates of these measures may generate misperceptions among some policy analysts to interpret higher values as preferable to lower values without examining the economic implications of water allocation scenarios since low values are not necesserily undesirable or high values are higher (Ahadi et al., 2013; Wichelns, 2002). Figure 3 highlights the complexity that might involved in water (re)allocation with competing stakeholders.

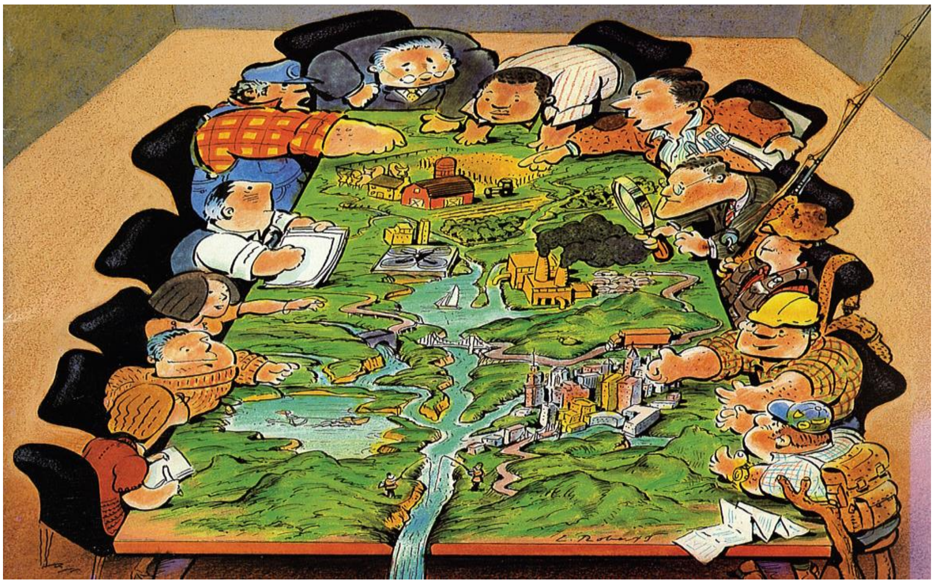

Figure 3 stakeholders studying river basin (reallocation) (adapted from Loucks & van Beek (2005))

2.6 Drivers of change

Dramatic population increase coupled with demographic change, and climate change impacts are part of the significant trends coming up in Nigeria and other parts of the world. These trends are projected to continue in future, with comparatively high rates in some cases. However, uncertainty is associated with future water management responses to population growth and climate change. The following subsections briefly discuss how they are related to the study area.

2.6.1 Population growth

Nigeria's population, currently the seventh largest in the world, is growing the most rapidly. Consequently, the population of Nigeria is projected to surpass that of the United States shortly before 2050, at which point it would become the third largest country in the world. Nigeria is the second (ordered by their expected contribution to global growth) among the countries expected to account collectively for more than half of the world's projected population increase over the period 2017-2050 (United Nations, Department of Economic and Social Affairs, 2017). Furthermore, Nigeria is the most populous country in Africa with a population of 182 million and has one of the fastest-growing economies in Sub-Saharan Africa; its gross domestic product (GDP) quadrupled between 2005 and 2015 (World Bank, 2017).

2.6.2 Climate change

The impacts of climate change caused by enhanced global warming have been well documented by the fifth assessment report of the Intergovernmental Panel on Climate Change (IPCC, 2014) which indicated that regional changes in climate, especially increases in temperature, have already affected a diverse set of physical and biological systems across the world. Due climate change, rainfall is predicted to fall off in most regions of the world including Africa (Faramarzi et al., 2013), which is also expected to affect evapotranspiration patterns as it is a function of rainfall and temperature. It has been associated with shifted growing seasons, threatened water sources and exacerbated food shortages. Unchecked climate change would reduce agricultural yields which, according to FAO (2009) could increase the number of malnourished children by 20 percent in 2050. Nigeria is on the global map, one of the highest producers of greenhouse gas emissions in Africa due to the continuous gas flaring going on in its Niger Delta region (Elum & Momodu, 2017). Consequently, some of these climate change impacts, such as flooding, drought and saltwater intrusion, have been witnessed in Nigeria (Elias & Omojola, 2015) and that most of the farmers have noticed changes in climate and have consequently adjusted their farming practices to adapt (Tambo & Abdoulaye, 2013).

Assessment of climate change impacts mainly relies on climate model outputs, derived from either General Circulation Models (GCMs) (or Earth System Models (ESMs)) or Regional Climate Models (RCMs). The downscaled outputs are then used to evaluate future climatic changes and to drive other sector-specific models for climate change impact studies. Results from these studies are used by policymakers to support decisions on climate change adaptation measures (Lutz et al., 2016). In Niger River basin located in western Africa, projections from an ensemble of 38 GCM model runs under the median A1B CO_2 emission scenarios was done by Grijsen et al. (2013). The results revealed no upward trend in precipitation until 2050 and by 3% in 2070, while temperatures showed a steady increase on average of 2.1°C (8%) by 2050. Projected temperature increases vary between +1.0°C and +3.0°C by 2050. The implication is an increase of potential evapotranspiration by about 5% for a 2.1°C temperature rise and a similar increase in irrigation requirements. A similar result was obtained for Nigeria (Osborn, Wallace, Harris, & Melvin, 2016). The study proposed warmings from 1 to 4°C for a fixed global warming of 2°C above the 1961-1990 baseline (Figure 4). In another study, driven by an ensemble 18 regional climate projections, Aich et al. (2016) projected changes in flood magnitudes in the Niger River Basin between base period (1976–2005) and near future period (2021–2050). Results revealed increases of flood magnitudes in the basin because of increasing river flows with a mean increase above 5%. Similarly, studies elsewhere projected an increase in annual mean precipitation of 16% by mid-century to 18% by the end of the century over the Indus basin (Garg, Aggarwal, Nikam, & Thakur, 2013). Table 4 shows the result of projections of ensemble 38 GCMs model runs for Niger River Basin.

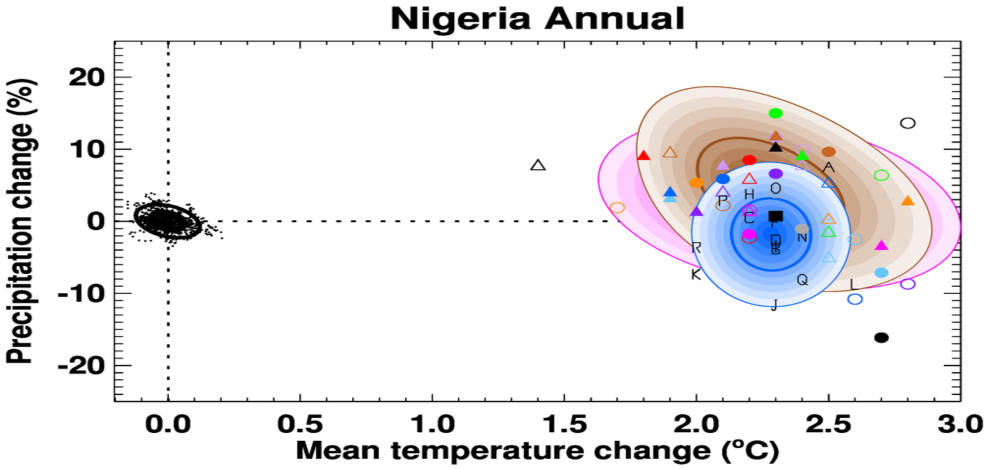

Figure 4 Projected Nigerian average temperature and precipitation (Source: Osborn et al. (2016))

Table 4 projected climate changes (2050; A1B) (Source: Grijsen et al. 2013)

Variable	**Min.**	**20%**	**Mean**	**80%**	**Max.**	**Standard Deviation**
Temperature (°C)	1.2	1.6	2.1	2.6	2.9	0.5
Precipitation (%)	-5.8	-3.5	1.4	4.5	13.7	4.5
Annual runoff (%)	-19.5	-13.2	-1.9	4.7	32.3	10.9
Annual PET (%)	2.6	3.6	4.7	5.8	6.7	1.1

The Nigerian scenario has shown various climate change impacts. According to World Health Organization (WHO), considering a high emissions scenario (RCP8.5), mean annual temperature is projected to increase by an average of about 4.9°C from 1990 to 2100. If emissions decrease fast (considering RCP2.6), the temperature rise is limited to about 1.4°C. Under the scenario, the number of days with very heavy precipitation (20 mm or more) could increase by about three days on average from 1990 to 2100 (WHO/UNICEF, 2015). It is important to note that Nigeria is made up of different climatic zones. Maps (Figure 5a and 5b) indicate the geographic variations showing the 1961-1990 average annual temperature and precipitation across the country or region (Osborn et al., 2016). Figure 6 shows national average 1961-1990 temperature and precipitation for each month of the year.

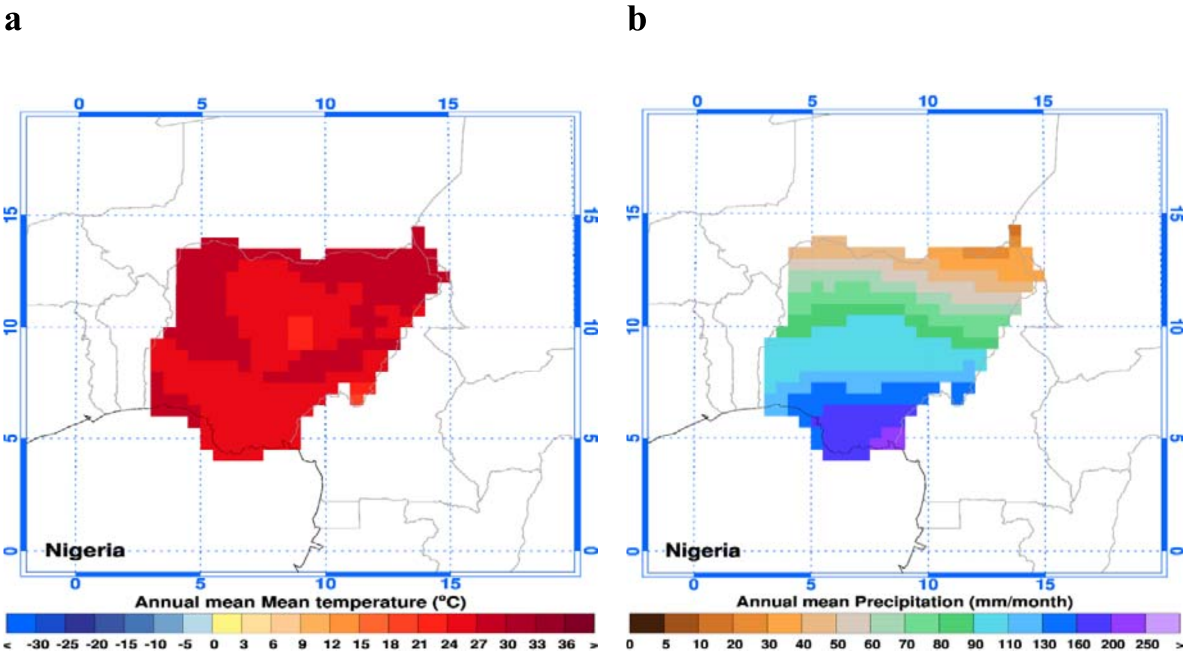

Figure 5 (a) Annual mean temperature (1961-1990) (b) Annual mean precipitation (1961-1990)

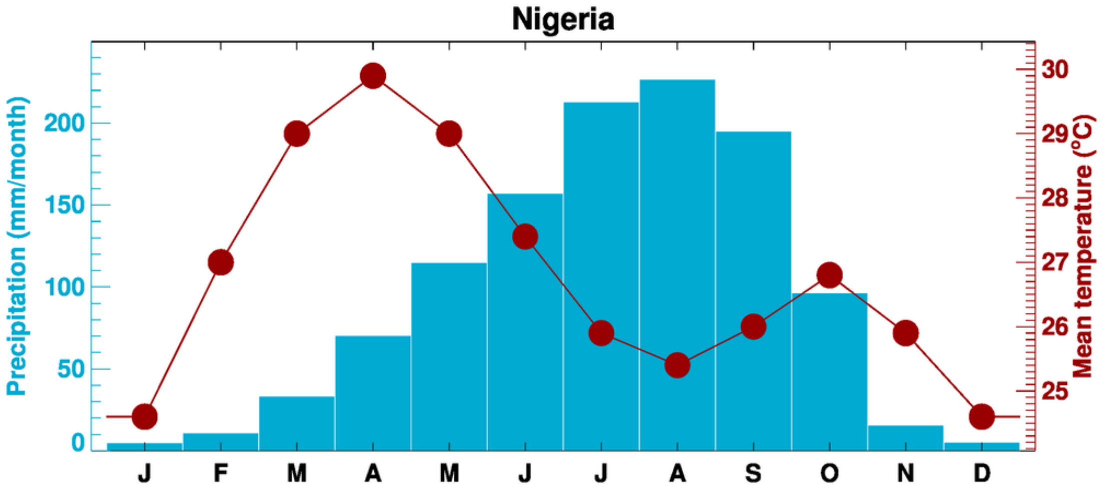

Figure 6 National average temperature and precipitation for each month (1961-1990)

At HJKYB level, Odunuga, Okeke, & Omojola (2011) predicted water balance deficit under different scenarios, and results revealed that a water deficit increase of 0.97% and 6.21% for the 50-year medium and high emission climate change respectively, for Kano relative to the 2006 water balance. This indicates that there will be a reduction in water availability in the basin. In another study, Odjugo (2010) analysed mean annual and monthly temperature and rainfall data for 105 years in Kano and the results show that while temperature increased by 1.1°C, rainfall decreased by 81 mm. It should be noted that quantity of precipitation per year is very different from its distribution annually. Most of the times, climate change is intensifying, meaning that the increase in annual happens with fewer precipitation events, as observed in Kano by Mohammed, Abdulhamid, Badamasi, & Ahmed (2015). They found out that although the trends of all the indices revealed an improvement in rainy condition except in the length of rainy season.

2.7 Sustainable Development Goals (SDGs)

The Sustainable Development Goals (SDGs), otherwise known as the Global Goals, are a universal call to action to end poverty, protect the planet and ensure that all people enjoy peace and prosperity. It is officially known as “Transforming our world: the 2030 Agenda for Sustainable Development” is a set of seventeen (17) aspirational “Global Goals” with 169 targets and 244 indicators (Table 5 and Figure 7) (United Nations, 2015). SDGs are a set of universal goals that meet the urgent environmental, political, and economic challenges facing the universe. The SDGs replaced the Millennium Development Goals (MDGs), which started a global effort in 2000 to tackle the indignity of poverty.

Table 5 the 17 Sustainable Development Goals (SDGs)

17 Sustainable Development Goals	
Goal 1	End poverty in all its forms everywhere
Goal 2	End hunger, achieve food security and improved nutrition and promote sustainable agriculture
Goal 3	Ensure healthy lives and promote well-being for all at all ages
Goal 4	Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all
Goal 5	Achieve gender equality and empower all women and girls
Goal 6	Ensure availability and sustainable management of water and sanitation for all
Goal 7	Ensure access to affordable, reliable, sustainable and modern energy for all
Goal 8	Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all
Goal 9	Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation
Goal 10	Reduce inequality within and among countries
Goal 11	Make cities and human settlements inclusive, safe, resilient and sustainable
Goal 12	Ensure sustainable consumption and production patterns
Goal 13	Take urgent action to combat climate change and its impacts
Goal 14	Conserve and sustainably use the oceans, seas and marine resources for sustainable development
Goal 15	Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss
Goal 16	Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels
Goal 17	Strengthen the means of implementation and revitalize the global partnership for sustainable development

In this context, goals like end poverty (goal 1), end hunger and promote sustainable agriculture (goal 2), ensure healthy lives and promote well-being (goal 3), and sustainable water management from local to global levels (Goal 6 and 14), mitigating climate change (Goal 13), and protecting ecosystems and forests (Goal 15) are directly related to water management.

Figure 7 Sustainable Development Goals (SDGs)

Nonetheless the immense progress in water development, the demands are still challenging to meet in many regions of the world. According to Steduto, Faurès, Hoogeveen, Winpenny, & Burke (2012) by 2025, 1.8 billion people are expected to be living in countries or regions with ‘absolute’ water scarcity, and two-thirds of the global population could be under ‘stress’ conditions. More than 300 million people in Sub-Saharan Africa do not have access to improved water, and close to 700 million lack access to improved sanitation facilities. In Nigeria alone, 71 million people continue to live without access to improved water, while 130 million people do not meet the Millennium Development Goal (MDG) standards for sanitation (United Nations General Assembly (United Nations, 2015). Hence, incorporating the goals in the process of design, planning and management of water resources is very crucial.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Location of the study area

This study is conducted in Kano River basin situated in Kano state, located between latitude 10° 30’ N and 13° N and between longitude 7° 40’ E and 10° 35’ E (as indicated in Figure 8 and 9). Kano River basin (KRB) is a sub-catchment of the Hadejia River situated in Northern Nigeria. It drains a catchment of 16,380 km^2 via the Hadejia-Jama’are River into the Lake Chad. Kano River has been part of the complex system of the Hadejia river basin in which two principal tributaries of Kano and Challawa rivers join to form Hadejia River.

Kano City (latitude 12° 03’ N and 8° 32’ E) is in the central watershed which separates the two main river basins in the metropolis (Figure 8). The Jakara River basin in the north comprising of Jakara River and its main tributaries – *Gogau, Tukurawa, Gwagwarwa, Rafin Mallam, Tsakama, Cijaki*, and *Getsi*. The Kano River basin lies to the south of the water divide and is being drained by Rivers Kano and Challawa, and their tributaries – *Watari, ‘Yarkuto, Tatsawarki*, and *Salanta* (Bichi & Anyata, 1999). Kano is the second fastest growing state in Nigeria with a population of approximately 10 million and about 60% of the population is located in urban areas (National Population Commission, 2010).

Kano River basin supports an estimated population of over 3 million people, most of whom rely directly on this water for their domestic supplies and livelihoods through irrigated farming, fishing, and livestock herding, transportation and industrial activities. The dam constructed on the river has a significant impact on the downstream part of the river. Tiga dam serves the KRIP via the Ruwan Kanya Reservoir downstream of the main canal from Tiga Dam and provides raw water for Kano City. The following subsections highlight the major hydro climatological variables found in Kano River basin.

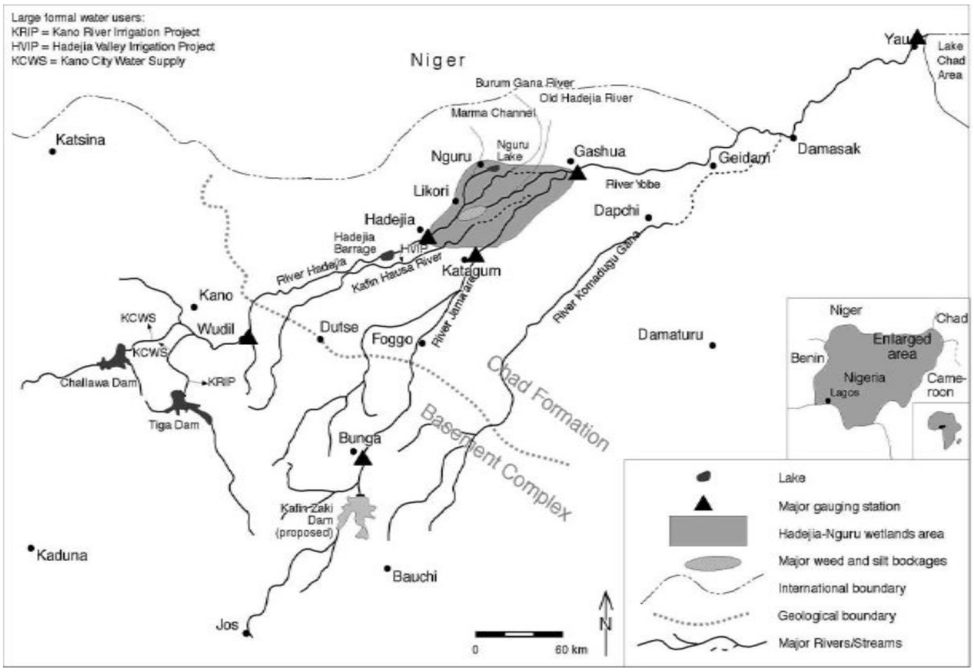

Figure 8 Kano River basin showing the main water users (KRIP and KCWS)

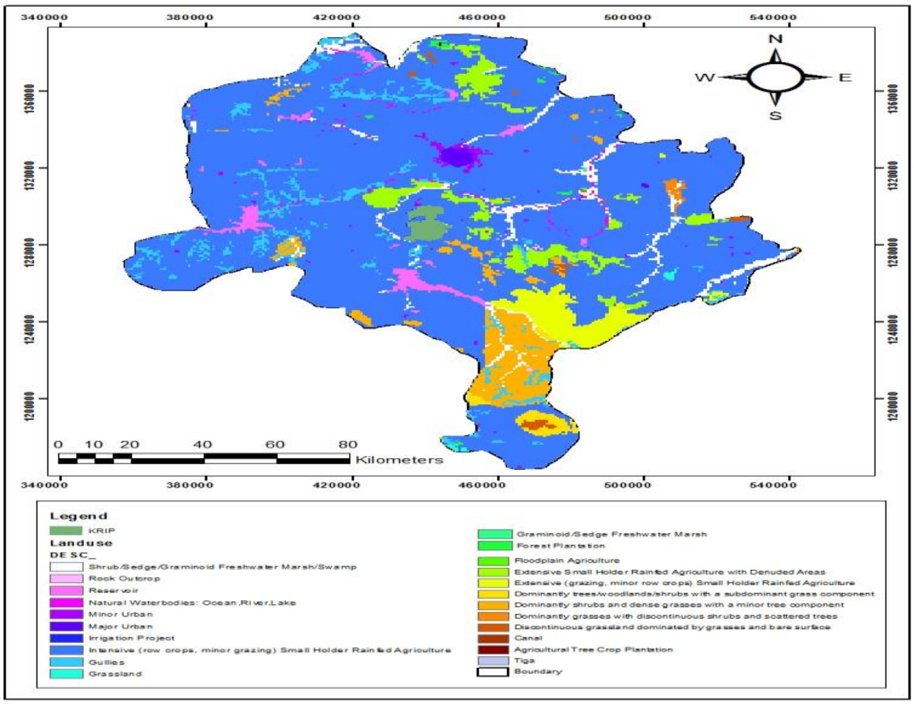

Figure 9 Kano state land use map

3.1.1 Climate and hydrogeology

There are four distinct seasons experience in Kano. These are; *Rani* (warm and dry), *Damina* (wet and warm), *Kaka* (cool and dry) and *Bazara* (hot and dry). There is a cool dry season from November-February, a hot dry season from March-May and a warm wet season from June-September. It is closely associated with the movement of the Inter-Tropical Discontinuity (ITD) zone. Basement complex of Precambrian rocks underlies the basin (Abdulhamid, Badamasi, & Mohammed, 2010). The topsoil consists of predominantly sandy loam covered by Aeolian sand derived from wind deposits with a thickness of about 5m in the upland and 10 m along the lowland plains.

The mean annual Rainfall is about 884 mm varying significantly from as low as 600 mm in the north to 1200 mm in the Southern tips. On the average, the wettest month is August which has the highest number of rainstorms and sediment generation. Mohammed et al. (2015) revealed that mean annual rainfall of the area is 897.7 mm, and maximum and minimum values are 1872 mm and 419.6 mm respectively. 1973 was the driest year of the period while 1998 was wettest. 1973 corresponds with severe 1973/74 drought that affects most of sub-Saharan Africa. The mean annual temperature in the area ranges from 26ºC to 32ºC, with the high diurnal temperature ranges of 13.1ºC and relative humidity of 17%-90%. Temperatures are highest in the late dry season in April and May with mean daily minimum temperatures of 24ºC and an average daily maximum of 38ºC. The coldest month is January with mean daily minimum temperatures of 13ºC and an average daily maximum of 30ºC. Most of the year has bright sunshine with the duration decreasing in the Harmattan season. Relative humidity varies from 13% in February to 94% in August. Evaporation estimates vary widely with different data sources, probably due to an inadequate definition of whether the rates quoted are open water evaporation (potential water evaporation E_o), evapotranspiration or corrected pan figures. However, evaporation is in the range of 3,500 mm to 4,500 mm per year (Parkman, 2000).

Rainfall is the primary source of aquifer recharge, i.e., the groundwater is recharged mainly from the runoff water contributed by the river. There is, however, very little information on the extent of groundwater recharge and the area covered. Thompson & Hollis (1995) showed that the mean groundwater recharge amounted to 33% of the total river flow input with local rainfall contributing only 13% of the water balance.

The combined action of climate and physiography influence the pattern of land use in the basin. This, of course, determines the soil type, availability of water, vegetation, etc. all of which determines what use the land can be put to. Most economic activities in the basin are greatly affected by the environmental changes that characterize the basin in recent times due to poor land and water resources management practices.

3.1.2 Effective runoff and river flow

Effective runoff of catchment system plays a significant role in water resources evaluation because it defined that component of rainfall that reaches the surface water drainage system. In Kano River basin, where rainfall is around 800 mm, runoff could be about 10%, i.e., 80 mm per year. This figure is consistent with other catchment runoff investigations in Northern Nigeria. These runoff coefficients, though, approximate are based on practical evidence from other studies in Northern Nigeria and provide a handy broad check on the likely runoff into existing reservoirs such as Tiga and Challawa Gorge (Parkman, 2000).

Following the seasonality of rainfall and the runoff characteristics outlined above, it is not surprising that nearly all unregulated rivers in Kano state are ephemeral. The drainage pattern is characterized by broad shallow river valleys obstructed with sand. However, after completion of Tiga dam, there has been a significant change in the regime of Kano River from ephemeral to perennial, as a result of the dry season releases from Tiga Dam, which are meant to supply water to KRIP and KCWS (Goes, 2002; Goes, 2001). Subsequently, annual runoff in Kano River at Wudil was reduced due to an increased in the water usage and evaporation losses from Tiga Reservoir.

The following subsections highlight the principal features found in Kano River basin.

3.2 Main features of Kano River basin

3.2.1 Tiga dam

Tiga Dam is a zoned earth-fill embankment dam. It has a nominal height of 48 m from the bottom of its cut-off trench (lowest foundation level) and embankment height of 33 m when measured from the downstream river level. The embankment is approximately 6 km long. The original spillway is an uncontrolled, concrete ogee spillway located on the left flank having a total length of 447 m. It is divided into a central, lower section of 122 m. This was the original full supply level, and the remaining 325 m of the spillway is 300 mm higher than the central section. Because of concerns about the safety of the dam since construction, the auxiliary emergency spillway embankment to the left of the spillway was adjusted. This new channel is approximately 200 m wide, and at a level of 523.87 m, that is 3.43 m lower than the original level. Its original capacity was 1, 974 Mm^3 and the surface area 189 km^2. After the lowering of the full supply level, the capacity was reduced to 1,374 Mm^3 (HaskoningDHV, 2015). Table 6 highlights the main features of Tiga dam and Figure 10 shows Tiga dam in Kano River basin.

Table 6 General dimensions of Tiga dam

Name	**Tiga Dam**
Location	11°30'03 N 8°26'52"E
Wall Type	Zoned earth fill embankment (assumed)
Crest Length	6, 000 m (embankment only)
Crest Width	Design width 12 m, but varies
Upstream Slope (V:H)	1:3
Downstream Slope (V:H):	1:2.5
Wall Height (LFL to NOC):	48 m
Catchment Area	6, 553 km^2
Wall Height (River to NOC)	33 m
Level of NOC	530.96 m
Full Supply Level	523.87 m
Gross Full Supply Capacity	1, 374 x 10^6 m^3
Owner	Hadejia Jama'are River Basin Development Authority (since 1976)
Designer and Constructor	Water Resources Division (WRD) of the Kano State Ministry of Works and Surveys, later Water Resources and Engineering Construction Agency (WRECA)
Construction Period	1971 to 1974 (approximate)
Total volume of fill material	9.18 x 10^6 m^3

Sources: HaskoningDHV (2015); HJRBDA Annual Reports (2013)

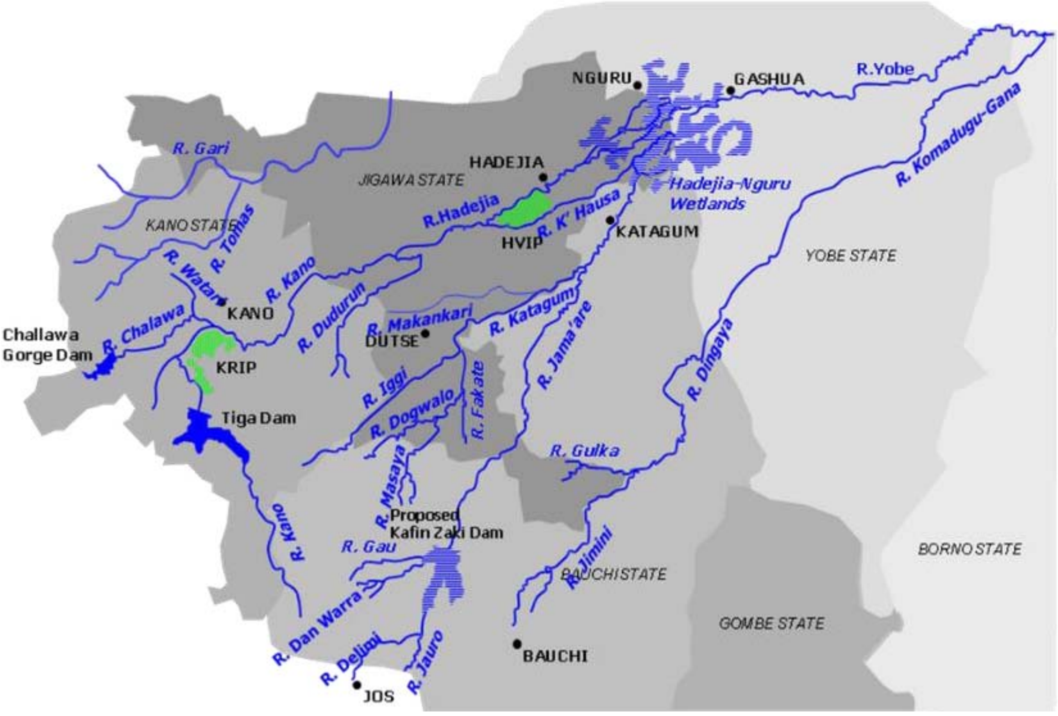

Figure 10 Tiga dam in Kano River basin

3.2.2 Kano River Irrigation Project (KRIP)

KRIP was established by Kano state government in 1970, with the aim of developing over 62,000 ha of agricultural land for crop production by irrigation using water from Tiga Dam that impounds Kano River. The project is located about 35 km south of Kano City between longitudes 8° 30’ and 9 °40’ E and latitudes 11° 30’ and 12° 03’ N, specifically in Bunkure, Kura and Garun Malam local government areas with project office at Kura (Figure 11). The estimated size of the irrigated land varies according to different research groups; 13,400 ha to 19,107 ha and recently to 22,000 ha. The phase I of the project commenced operation in 1976 after it was formally taken over by the Hadejia-Jama-are River Basin Development Authority (HJRBDA) and Phase II is far from the reality.

The following sections present the elements of the KRIP system, from upstream to downstream:

- Tiga Dam and Reservoir;
- Main canal system - including the Ruwan Kanya Dam and Reservoir – supplying water to 50 sectors (ultimately);
- East branch canal system, at present supplying water to 11 sectors and ultimately to 18 sectors;
- Gayare branch canal system supplying water to 3 sectors, and West branch canal system, at present supplying water to 27 sectors and ultimately to 29 sectors.

The irrigation water from the Tiga Reservoir is discharged into the main canal which is about 12 km long. The water enters the project area at the main division works at Garum Baba. It is distributed between the West and East branch canals. From the branch canals, the water flows into the laterals via sector turnouts. From the lateral canals, the water flows through a distributary turnout into the distributary canal, which supplies the blocks. From the distributary canals, the water runs through a field turnout into the field channel. All the turnouts are provided with undershot measuring gates to ensure accurate distribution. Irrigation during the night is out of the question. To keep down construction costs and to avoid management problems with a system that functions only for 10 or 12 hours per day, night storage reservoirs were designed at the secondary level. Night and day the water will flow uninterruptedly into the branch and lateral canals. The distributaries operate only in the day-time; some receive so-called 'night water' from a night reservoir, some 'day water' directly from a lateral canal (NEDECO, 1976).

Main agricultural outputs produced in the basin include onion, sugar cane, tomato, carrot and pepper, garden egg, wheat and rice in the dry season; while in the wet season sorghum, millet cowpea, groundnuts and cassava are the main products. Table 7 highlights the main characteristics of KRIP.

Table 7 Main features of KRIP

Characteristics	**KRIP**
Planned irrigable area (ha)	22,000
Developed irrigable area (ha)	16,500
Average actual cropped Area in 2011, 2013 and 2014 (ha)	13,227
Major crop	Rice
Major crop yield (Tons/ha)	3.2
Second major crop	Tomato
Second major crop yield (Tons/ha)	15
Irrigation Water	
Water sources	Tiga Dam
Abstraction method	Gravity
Average annual rainfall (mm)	750
Water charges (Naira/ha)	2,500
Length of main canals (km)	18
% Lining of main canals	80
Length of branch canals (km)	56
Length of secondary canals (km)	320
Length of main drain (km)	320
Length of field canals (km)	1,120
Length of field drains (km)	1,120
Length of collector drains	496
No. of night reservoirs	8
No. of field structures	16,000
Length of service roads (km)	816

Sources: HaskoningDHV (2015); HJRBDA Annual Reports (2011)

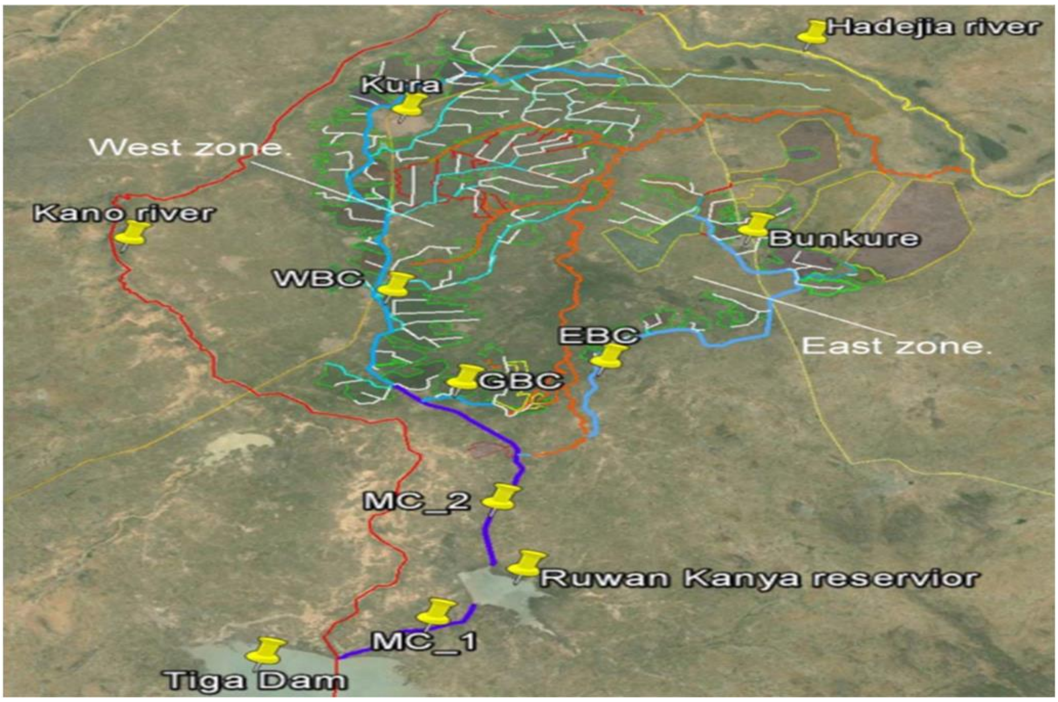

Figure 11 Kano River Irrigation Project (KRIP) (Source: HaskoningDHV 2015)

3.2.3 Ruwan Kanya Reservoir (RKR)

Ruwan Kanya Dam is an earth-fill embankment dam that floods a valley along the link canal from Tiga Dam to KRIP. Located to the northeast of Tiga Dam, it approximately spans 4.8 km from the Tiga outlet, along the link canal from Tiga Dam to KRIP (Figure 11). It was considered the most suitable alternative instead of having a link canal section that follows the contours around the valley perimeter at that time. Hence, it was constructed in place of an inverted siphon or a canal (pipe) bridge that was also considered at that time. The dam was built in 1974-1975, after the completion of the Tiga Dam. The capacity of the dam is indicated as 33 Mm^3, but more likely this is about 70 Mm^3 (HaskoningDHV, 2015). However, HJRBDA Annual Reports (2011) reported 57.6 Mm^3 as its storage capacity. Table 8 shows the main features of RKR.

Table 8 General dimensions of Ruwan Kanya dam

Name	Ruwan Kanya Dam
Location	11°30'03 N 8°26'52"E
Wall Type	Zoned earth fill embankment (assumed)
Crest Length	3 500 m (embankment only)
Crest Width	9.14 m (maximum)
Upstream Slope (V:H)	1:2.5
Downstream Slope (V:H)	1:2
Wall Height (LFL TO NOC)	22 m
Wall Height (TOE TO NOC)	15 m
Catchment Area	136 km^2
Level of NOC	512.41 m (varies)
Full Supply Level	509.35 m
River Level	503 m (approximate, at spillway)
Foundation Level	492 m (approximate)
Gross Full Supply Capacity	57.6 Mm^3 (33 or 70 Mm^3 sources of information differ)
Purpose	Balancing storage
Owner	Hadejia Jama'are River Basin Development Authority
Designer and Constructor	Water Resources Division (WRD) of the Kano State Ministry of Works and Surveys, later Water Resources and Engineering Construction Agency (WRECA)
Construction Period	1974 - 75

Sources: HaskoningDHV (2015); HJRBDA Annual Reports (2013)

3.3 Methodology

The methodology consists of four steps: (1) data collection (2) designing the options to be evaluated (3) employing Sefficiency method for performance assessment, and (4) developing case scenarios and sensitivity analyses of results due to a varying climate change and population growth.

3.3.1 Data collection

A wide range of study methods, including semi-structured interviews, a case study of the irrigation project, personal correspondence, field visits, observation and secondary data was used in this research. The water systems under study comprised of subsystems that serve the purposes of agricultural, environmental and urban water supply. Basic data collected include hydrological and hydraulic data, existing water allocation practices and water demand, uses and consumption patterns. Data was collected from previous project documents, published peer-reviewed papers, interviews with stakeholders, plausible reasoning and calculations. The data for KCWS (both raw and treated water) for 2014 to 2016 was obtained from planning, research and statistics division of Kano state water board (KNSWB). Monthly effluent discharge monitoring reports for industries were obtained from pollution control laboratory of Kano state ministry of environment. Beneficial weights were assigned based on the outcome of the interviews with stakeholders; management of KNSWB, Kano city residents, industrialists, and consultants. Quality weights were derived from previous project documents and peer-reviewed journals.

Data on wastewater collection and treatment are scarce particularly in developing countries (Sato, Qadir, Yamamoto, Endo, & Zahoor, 2013). In Nigeria most cities are not provided with wastewater collection and treatment facilities and the wastewater produced from houses is mainly treated in septic tanks. In Kano city, sullage is frequently discharged to open drains which are mainly dug by house owners, and generally unlined without proper gradients frequently served as combined sewers for stormwater, kitchen and bathroom effluents. All the open sewerage from central and north Kano city end up in Jakara River.

3.3.1.1 Study area selection and reconnaissance survey

Kano River basin was selected as the study area, and reconnaissance was carried out. This was to gather initial information regarding the extent of the area to be studied and other physical characteristics of the area. This helped in planning the field data collection.

The reconnaissance survey facilitated the followings;

1. Refining and finalizing the selection of study area;
2. Collecting preliminary information on the number and location of stakeholders;
3. Identifying administrative requirements based on local conditions and planning for field data collection.

An observation was made and note taken of physical and socio-economic features, issues, problems, threats and opportunities that might be encountered during the field data collection. Materials used include; Field maps, digital camera, pens/pencils and others.

3.3.1.2 Hydrological and hydraulic data

Data on hydrologic variables that are crucial for analyses and forecasting was collected. The data was found in various publications of state and federal agencies, research institutes (agricultural, water resources and geologic), universities (through research centres) and other organizations. However, the data found was not recent.

Data obtained include;

i. Daily and monthly average rainfall data
ii. Minimum and maximum temperature
iii. Relative humidity
iv. Solar radiation
v. Wind speed

The data was obtained from the following institutions;

i. Hadejia-Jama’are River Basin Development Authority (HJRBDA)

ii. Kano State Ministry of Water Resources (KSMWR)
iii. Mallam Aminu Kano International Airport (MAKIA) NIMET synoptic meteorological station
iv. Kano State Agricultural and Rural Development Authority (KNARDA)
v. Water Recourses and Engineering and Construction Agency (WRECA)
vi. Kano State Ministry of Environment

It is challenging to estimate the contribution of various factors (rainfall, seepage from canals, percolation from farmers' fields, groundwater abstraction) affecting the water balance in the study area. However, crop evapotranspiration requirements were estimated using CROPWAT 8.0 (Swennenhuis, 2010). Other flows were documented in various reports and papers.

3.3.1.3 Data on existing water allocation criteria

Data relating to when and how much water is allocated to the various water users in the basin are lacking. Water demands are met irrespective of upstream and downstream order without regard to priorities. All in all, the allocation is supply driven.

3.3.1.4 Water demand and use patterns of urban and agricultural uses

The population of Kano metropolis based on the most recent data, i.e., Census Population 2006 was obtained. The domestic consumption for different housing type and income proposed by Parkman (2000) was adopted. Domestic and industrial water demand was determined by population and per capita use statistics. Future population distribution was determined from projections of the percent change in total urban population from 2017 to 2050. Daily average industrial and institutional water uses were estimated as percentages of daily average domestic water use, as adopted by other studies, such as (JICA et al., 2014). Losses were estimated and incorporated based on Parkman (2000). Agricultural demands were compared with results obtained from a recent study that used CropWat 8.0 to estimate the crop water requirement

(HaskoningDHV, 2015). Details regarding the methodology used are discussed in individual chapters.

3.3.1.5 Determination of beneficial and quality weights

This was achieved by the active participation of stakeholders that are significant players in the basin, as each activity has different weight for different stakeholders. Assigning weights to different water flow paths (both beneficial and quality) is crucial for sustainability, and needs a compromise between different stakeholders. The weights were assigned considering all the impacts of these activities on the total system itself and the environment.

Management's and farmers' perception of the beneficial use of water (beneficial weights) were gathered. A sample of forty-five farmers and five management staffs were selected through stratified random sampling and interviewed in March–April 2016. The sample covered the head, middle and tail-end sections of KRIP. Interviews were also conducted with other stakeholders such as water users (non-farmers) and consultants. A second interview was re-scheduled and conducted in March-April 2017. Besides beneficial weights, questions during the interviews pertained to the management of water resources by HJRBDA and farmers' satisfaction and perception on water availability and allocation to different users. The respondents assigned different weight values to each of the variables based on their experiences, knowledge, and perception. The procedure followed to ensure the validity and reliability of the results obtained is outlined in Galvin (2015).

3.3.2 Options for evaluation

Options considered for evaluation are performance assessments of the two principal water users in the basin and taking account the environmental flows.

3.3.2.1 KRIP model (M1)

In this option called KRIP model, WUS is defined as KRIP including the main canal and the RKR. KRIP is discussed in detail in chapter 4.

3.3.2.2 Kano River model (M2)

In this analysis, WUS is defined as Kano River including the Tiga dam until downstream just before the point where releases are emptied into Hadejia River. In this option, water supplied by KNSWB is the focus because it is centralized, in other words, manageable compared to other sources such as groundwater and rainwater harvesting that is somewhat distributed and hence difficult to assess. However, it should be noted that KNSWB could only provide 50% of the total water demand for Kano city. Kano River is discussed in detail in chapter 5.

3.3.3 Employing Sefficiency model for performance assessment

Sefficiency is used to determine the performance of the various options considered. Sefficiency advances systemic and comprehensive performance indicators based on a universal principle that integrate differentials and trade-offs of water quantity, quality and beneficial uses at multi-level management and planning with climate descriptors and stakeholder enablers. The development of Sefficiency can be categorized into three major levels: macro, meso and micro, which can be found in Haie & Keller (2012) and further expanded in Haie & Keller (2014). What follows is a summary of the main structure.

To use the law of conservation of mass (water balance), water use systems such as a city, farm or basin is defined by characterizing the associated water types (WaTs) and the corresponding attributes. Water Paths (WaPs) are actual or real water flows in a system under analysis. WaTs are types or classes of inflow and outflow of water balance that must be expanded to WaPs because a water type can lead to more than one flow path. Set of flow types are defined within the context of water balance which seems to be general enough for most water use systems, such as the one shown in Figure 12. The different flow types have the same unit of measurement (such as ha-m or m^3). They are summarized in Table 9.

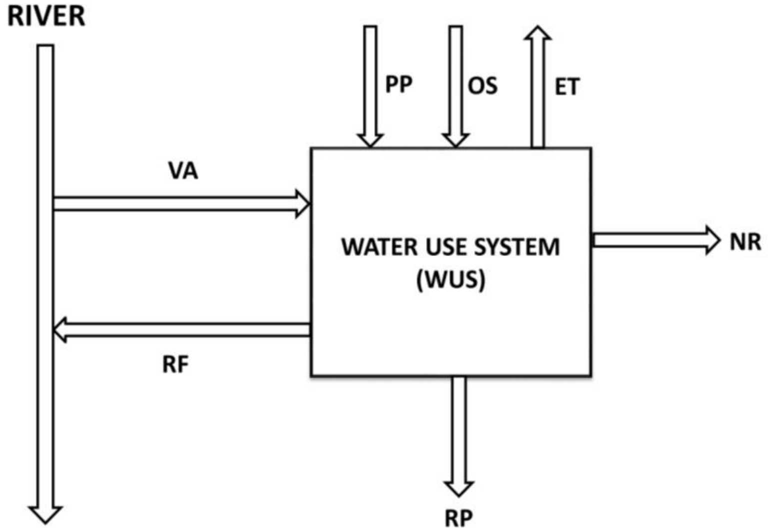

Figure 12 General schematic of water use system (WUS)

Table 9 Basic flow types of water use system

Variables	**Description**
ET	Evapotranspiration
NR	Non-reusable
OS	Water from other sources
PP	Total precipitation
RF	Return flow
RP	Potential return (does not return to the main source)
VA	Abstracted/applied water from the main source
VD	Volume of water downstream after return flow in the main source
VU	Volume of water upstream before abstraction in the main source
V1	Volume of water at section 1 (VU or VA)
V2	Volume of water at section 2 (VD or RF)

Two attributes for each flow path is defined, namely, water quality and benefits; as such Sefficiency depends on three pillars, i.e. quantity, quality, and beneficial aspects of water. The two attributes of flow paths mentioned earlier set up a usefulness criterion Haie & Keller (2012), as defined in Equation (2).

$$\begin{aligned} X_b &= W_{bX} * X \\ X_q &= W_{qX} * X \\ X_s &= W_{sX} * X \\ W_{sX} &= W_{bX} * W_{qX} \end{aligned} \qquad \textbf{(2)}$$

X can be any flow, such as VA or RF (Table 9). W is the corresponding weight on a flow path for its beneficial (b), quality (q) or useful (s) attribute. W_{bX} and W_{qX} are taken as independent, for example, the beneficial weights are set without considering the quality weights. In other words, W_{bX} values are set by assuming W_{qX} values to be equal to one. In relation to water variables, one can readily designate two basic flow paths and two combined ones: evapotranspiration (ET), non-reusable water (NR), consumption (C) and effective consumption (EC), respectively. ET is outflow that is generally calculated via approaches such as Penman-Monteith equation. It is through ET that various climate factors such as temperature are incorporated into efficiency indicators and equations. NR is the other outflow that is non-reusable including evaporation, virtual water embodied in various products etc. The combination of ET and NR is called consumption (C), which is the total quantity of outflow not available for reuse.

EC is the total amount of water not available for further reuse. It includes C but also the differences in the beneficial and quality attributes of all the flow paths, hence conveying the degree to which water systems make water non-reusable depending on the purpose of the water path. For example, a kind of polluted return flow may be reusable for irrigation purposes but not for human consumption. Two other generic outflows are set in the water balance (Figure 12): return flow (RF) and potential return (RP), together called return (R). RF is the portion of the applied water returned from the water system to the source of abstraction. RP is water returned from a water system to the environment outside of it (not returned to its source of abstraction) including runoff; deep percolation; seepage; spills; leaching; etc. OS (other sources) is inflow from sources other than the main source. If the main source is a river, as in Figure 12, OS could be water from groundwater, from another basin, or from other inflow. The remaining basic variables are self-explanatory and are defined in Table 9. Obviously, not every water use system has all the flow paths schematized in Figure 12, but assigning zero to a flow type makes the process transparent with responsibility. The change in storage of a water system is mostly zero for the period of analysis, but if not, a combination of R and OS describes the required change in storage (Haie & Keller, 2014). Integrating the basic flows and applying the usefulness criterion to system flow paths yield an expanded terminology, as defined in Table 10. For example, it shows that the total inflow (I) into a system is the sum of VA, PP and OS (as shown in Figure 12), and if we apply the usefulness criterion to I, then we get the total useful inflow (UI).

Table 10 Combining basic water flow path types (WaTs) and applying a Usefulness Criterion

Symbol	Expression	Description
I	VA + OS + PP	Inflow
R	RF + RP	Return
C	ET + NR	Consumption
O	C + R	Outflow
UI	I_S	Useful Inflow
UR	R_S	Useful Return
UC	C_S	Useful Consumption
UO	O_S	Useful Outflow
EC	$(I - R)_S$	Effective Consumption

Table 10 shows that consumption (C) is the portion of outflow (O) from a WUS (e.g., an agricultural area, an urban zone, a basin, a region) that does not return to the basin for further reuse. In the Sefficiency framework, this quantity-based definition is extended to include quality by employing the concept of a Usefulness Criterion (equation 8), and by utilizing the word effective in the terminology. This generalization gives a total value called effective consumption (EC), which is the portion of useful outflow (UO) from a WUS that effectively is not available for reuse. For example, water flowing into a WUS (e.g., V1) is degraded as it leaves the system (e.g., V2), causing a decrease in its effective and real availability for reuse. In other words, any pollution increase adds to the effective consumption of a WUS, which should be decreased notably in water-scarce regions.

The following equations represents different levels of Sefficiency keeping in mind that the subscript S [defined relating to Equation (3, 4 and 5)] applies to all variables within the brackets.

The equation are as follows;

$$\boldsymbol{MacroEs} = \left[\frac{\boldsymbol{ET + NR + i(VD + RP)}}{\boldsymbol{VU + OS + PP - c(VD + RP)}}\right]\boldsymbol{s} \tag{3}$$

i + c = 1 with *i, c* ∈ {0, 1}

$$\boldsymbol{MesoEs} = \left[\frac{\boldsymbol{ET + NR + i(RF + RP)}}{\boldsymbol{VA + OS + PP - c(RF + RP)}}\right]\boldsymbol{s} \tag{4}$$

$$\boldsymbol{MicroEs} = \left[\frac{\boldsymbol{ET + NR}}{\boldsymbol{VA + OS + PP}}\right]\boldsymbol{s} \tag{5}$$

The two indices i (inflow models) and c (consumptive models) correspond to two water totals: useful inflow and effective consumption. Each index is either zero or one, with their sum equal to one. Their appearance before MesoE shows the type of indicator. For instance, iMesoE means meso-efficiency calculated as an inflow model (i = 1, c = 0). The necessary minimum conditions in using Sefficiency are that useful outflow must be less than useful inflow and useful consumption must be less than effective consumption. Both assumptions are met in any kind of agricultural or urban setting. Finally, MesoEs includes return flows in its calculation and considers the impacts of the system on the downstream users, including environmental flows.

The general format of the above equations using the terminology given in Table 10 gives equation (6), the condensed form of the readily understandable equation of Sefficiency:

$$\boldsymbol{Es} = \left(\frac{\boldsymbol{C} + \boldsymbol{i}\,\boldsymbol{X}\,\boldsymbol{R}}{\boldsymbol{I} - \boldsymbol{c}\,\boldsymbol{X}\,\boldsymbol{R}}\right)\boldsymbol{s} = \frac{\boldsymbol{UC} + \boldsymbol{i}\,\boldsymbol{X}\,\boldsymbol{UR}}{\boldsymbol{UI} - \boldsymbol{c}\,\boldsymbol{X}\,\boldsymbol{UR}} \qquad \textbf{(6)}$$

where i and c are the inflow and consumptive models. For example, iE_S is an inflow Sefficiency indicator (i.e., i = 1), which gives the percentage of total useful inflow which is useful outflow. cE_S (i.e., c = 1) provides the percentage of effective consumption that is useful consumption. As such, $iE_S > cE_S$ (the impossibility of their equality is explained by Haie & Pereira (2015).

3.3.3.1 Steps in Sefficiency calculation

One crucial point regarding Sefficiency completeness is to be sure that the nine WaTs shown in Figure 12 and defined in Table 9 are explicitly accounted for. These are the types or classes of inflows and outflows of water balance that must be expanded to WFPs because a type can lead to more than one flow path. However, due to such difficulties, it is possible but not recommended to exclude macro-level analysis, which suggests that, at a maximum, seven WFTs (omitting VU and VD) are needed for a water and management design.

The following steps were sequentially applied in this study in order to find the Sefficiency of the different WUSs, with the first nine being the most crucial (Haie, 2016):

1. Define the Water Use System (WUS) to be analysed
    i. Define its main objectives
2. Identify the main source of water
3. Reason through Water path Types (WaTs) that are equal to zero
4. Draw the schematics of the WUS with all its WaPs
5. Reason through WFPAs that are equal to zero or one

6. Estimate the quantity values for WaPs
7. Verify water balances
8. Specify stakeholders for each of the WaPs
9. Estimate WaPs Attributes
10. Calculate Sefficiency
11. Do sensitivity analyses
12. Develop scenarios
13. Propose solutions, preferably, using adaptive processes

Start over, if not reasonable / acceptable

The results of each option considered are presented in subsequent chapters. However, the typical schematic showing water flows among major water users in Kano River basin and Generic I/O symbols and their descriptions are presented in Figure 13 and Table 11, respectively.

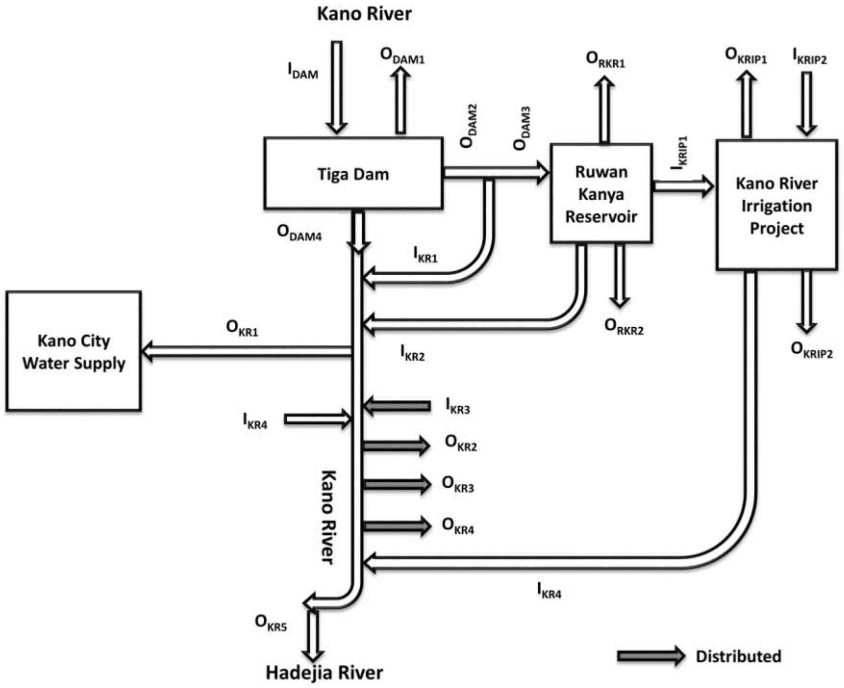

Figure 13 Typical schematic showing water flows among major water users in Kano River basin

Table 11 Generic I/O symbols and their descriptions

Generic I/O symbols	**Description**
I_{DAM}	Average annual inflow into Tiga dam
I_{KR1}	Smaller Tiga outlets and by-pass outlet from irrigation canal
I_{KR2}	Spill from RKR to Kano River
I_{KR3}	Precipitation over Kano River
I_{KR4}	Wastewater form Kano Metropolis into Kano River
I_{KR5}	Return flows from KRIP
I_{RKR}	Inflow to RKR
I_{KRIP1}	Applied water to KRIP
I_{KRIP2}	Other sources from groundwater into KRIP
O_{DAM1}	Losses from evaporation and seepage from Tiga dam
O_{DAM2}	Irrigation canal to RKR
O_{DAM3}	Comsumptives uses by RKR
O_{DAM4}	Spill from Tiga dam
O_{KR1}	Applied water to KCWS
O_{KR2}	Non-beneficial evapotranspiration from Kano River
O_{KR3}	Seepage through Kano River bed
O_{KR4}	Evaporation from Kano River
O_{KR5}	Kano River downstream
O_{RKR1}	Evaporation from RKR
O_{RKR2}	Potential return from RKR (groundwater recharge)
O_{KRIP1}	Evapotranspiration from KRIP
O_{KRIP2}	Potential returns from KRIP (groundwater recharge)

Generally, the calculation of PIs is made for a period previously defined, for example, one year (the water supplier can choose other time frames according to his management needs). The period is called assessment period (Vieira et al., 2008). 2008).

3.3.3.2 CropWat 8.0

The reference evapotranspiration ET_o was calculated according to FAO Penman-Monteith method, using decision support software – CROPWAT 8.0 developed by FAO, based on FAO Irrigation and Drainage Paper 56 named FAO56 (Swennenhuis, 2010). FAO56 adopted the Penman-Monteith method as a global standard to estimate ET_o from meteorological data. Minimum and maximum temperature, humidity, wind speed and sunshine hours are the required meteorological data for estimating the reference evapotranspiration (ET_o). ET_c was estimated by multiplying ET_o by an empirical crop coefficient, K_c.

3.3.4 Developing scenarios and assessing sensitivity analysis

To develop future water allocation scenarios for Kano River basin, the possible factors that influence future water uses were identified and quantified here referred to as uncertainty. Case scenarios were developed for Kano River basin and KRIP based on two critical drivers of change: (i) population growth; and, (ii) climate change. Both population growth and climate change have an impact on increasing water demand, while climate change reduces water supply. The differences among the various scenarios were considered against the baseline or reference scenarios of KRIP and Kano River model.

First reference population and the growth rate were characterized upon which the future projections were based. Projections of future population based on 2006 census population of 2.8 million and growth rate of 3.5% for Kano metropolis was carried out for 2017, 2025, 2035 and 2050. Based on that and per capita consumption for domestic, commercial and industrial, future urban demand was estimated. Similarly, irrigation requirements were also estimated. Population scenarios were developed by keeping a variable of a parameter related to water demand volume (based on different percentages of supply) and keeping constant of the parameter related to the climate change (temperature and precipitation). This gave rise to M1P1, M1P2 and M1P3 for model 1 and M2P1, M2P2 and M2P3 for model 2.

Climate change scenarios were developed to cover a broad range of potential impacts in the models. The percentage increase in rainfall was considered based on the literature. It was also motivated due to the observation of increasing trends from historical data analysis and recent analyses. The projected change in rainfall and temperature were incorporated in the various flow paths for the two models keeping the population constant. As is the case for population, climate change scenarios were developed by keeping a variable of a parameter related to climate change and keeping a constant of the parameter related to the water demand volume (based on different percentages of supply). This produced M1C1, M1C2 and M1C3 for model 1, and M2C1, M2C2 and M2C3 for model 2.

Six population and six climate change scenarios were developed to cover a broad range of potential impacts. In addition to these twelve scenarios, the population scenarios have also been combined with climate scenarios, allowing a quantification of the impact of climate change and population growth simultaneously. In other words, by varying all the parameters related to climate change and water demand volume, the cumulative effects of previous alternatives could be determined. This results in another six different scenarios as M1B1, M1B2 and M1B3 for model 1 and M2B1, M2B2 and M2B3 for model 2.

Sefficiency was then used to assess the performance of Kano River basin under these influences. The subsequent chapters discuss the results as obtained in this study.

CHAPTER FOUR

SEFFICIENCY OF KANO RIVER IRRIGATION PROJECT (KRIP)

4.1 Introduction

Northern Nigeria is part of the semi-arid region of Africa known as the Sahel and many of its parts suffer from water scarcity issues. A major part of the available water resources is used for agricultural purposes in Kano River basin, and thus having an essential role in efficient use of water resources in the basin. The ever-increasing population, climate change and food production demand have placed a considerable pressure on Kano River Irrigation Project (KRIP), a major water user on Kano River, which is also the most upstream tributary of Yobe River flowing directly to Lake Chad which is an important transboundary basin in West Africa. Additionally, water supply to KRIP will unavoidably decrease after completion of hydropower station by Kano state government at Tiga dam, which will further worsen the situation due to hydropower unit operational problems. Increased water use performance is required to meet crop water requirements and maintain yields since the abstracted water is reducing. Irrigation systems may fail because of poor management operations in response to their performance (Hamid et al., 2011) and lack of investment in infrastructures (Pereira et al., 2012). However, in Nigeria, despite huge public investments in large scale irrigation projects water use efficiencies have been among the lowest in the world (Kolawole, 1989). Consequently, assessment of water use system has becomes a part of standardized procedures to improve the corresponding performance for optimal productivity and improved water management (Burt et al., 1997). Increasing water tension surrounding the allocation of water in Kano River basin necessitates efficient water management. This will help in reducing unsustainable releases from Tiga dam which significantly deplete the limited resources and increase its risk of failure, in terms of not meeting their supply commitments and their inability to release wet season flows to downstream users.

With regards to the research conducted in the field of irrigation water management, detailed discussions were documented on irrigation performance including proposed indicators (Bos, 1997; Haie & Keller, 2014; Jensen, 2007; Keller et al., 1996; Lankford, 2012; Mateos, 2008; Pereira et al., 2012; Seckler et al., 2003; Van Halsema & Vincent, 2012). The performance is often expressed with terms relative to efficiency. However, there are no widely accepted definitions, and the efficiency terms are used with different meanings relative to the various water use sectors and therefore possible misconceptions and misunderstandings arises (Haie & Keller, 2014; Jensen, 2007; Mateos, 2008; Pereira et al., 2012). Classical efficiency (CE) underestimate the true efficiency of existing irrigation systems for not considering issues like water reuse, difference between water use and water consumption, effect of use location in an irrigated district or a basin and water quality(Ghahroodi et al., 2015) and thus considered inappropriate and flawed for assessing hydrological impact in irrigated area. Alternative terms were proposed and CE has been replaced by a modern formulation called effective efficiency and net efficiency (Keller et al., 1996) which consider the abovementioned hydrological issues as well as environmental and ecological interactions (Haie & Keller, 2008; Masseroni, Facchi, & Gandolfi, 2016). Haie & Keller (2008) further analysed the usefulness of effective efficiency. Lankford (2012) introduced the term 'basin allocation irrigation efficiency' utilizing fractions and effective efficiency, and 'socialized localized irrigation efficiency', utilizing classical efficiency. However, the combined application of these concepts is preferable (or rather necessary) for improving water management (Ghahroodi et al., 2015; Lankford, 2012). Other authors proposed replacing the term efficiency by the terms such as consumed fraction and water productivity (Frederiksen & Allen, 2011; Molden & Sakthivadivel, 1999; Perry et al., 2009) based on principle of water accounting. Haie & Keller (2012) proposed Sefficiency based on a universal principle that integrates water quantity, quality and beneficial uses at multi-level management and planning with climate descriptors and stakeholder enablers.

Irrigation water management is also related to socio-economic and political issues (Gain & Giupponi, 2015; Vilanova et al., 2015), as such authors have put strong emphasis on stakeholder and public participation (Dejen et al., 2012; Gomo et al., 2014; Kono et al., 2012; Kuscu et al., 2009; Sam-Amoah & Gowing, 2001; Setegn et al., 2011; Yohannes et al., 2017) for ensuring accountability in a transparent process of decision making, including in Nigeria. Performance assessments have been done from different perspectives (e.g. researchers, donors, farmers, etc.) with least attention given to one of the fundamental stakeholder – farmers (Sam-Amoah & Gowing, 2001). This is particularly important because farmers perceive problems, practices and objectives differently from non-farmer water managers (Pereira et al., 2012). In terms of quantification, field experiments have been generally employed to quantify irrigation water management but are often expensive, time-consuming and site specific (Sam-Amoah & Gowing, 2001). Thus, simulation models based on GIS/remote sensing were developed to support irrigation management (Jiang et al., 2015; Singh et al., 2006). However, in the case of Nigeria (also similar case in Ethiopia), Gomo et al. (2014) identified resource constraints and the small size of individual irrigated plots as the reasons for not using methods like remote sensing.

Based on the currently available literature, previous studies of KRIP were mainly focused on water quality (Bichi & Anyata, 1999), appraisal of water resources applications (e.g., water resources allocation, domestic usage) and land cultivation (Sangari, 2006), soil fertility evaluation (Jibrin, Abubakar, & Suleiman, 2008), examination of rate of sedimentation in conveyance canals (Tukur, Olofin, & Mashi, 2013) and groundwater recharge estimation (Sobowale, Ramalan, Mudiare, & Oyebode, 2014; Sobowale, Ramalana, Mudiare, & Oyebode, 2015). However, none of the proposed studies are related to performance of KRIP as a water use system integrating stakeholder participation.

In light of these considerations, this chapter aims at evaluating the performance of KRIP at meso-level. Meso-efficiency (MesoE) is considered because it includes return flows in calculation, i.e. considering the impact of the system on the downstream users, including environmental flows. Due to its great importance, a discussion on differences of perception of water management and efficiency between farmers and managers (policy- and decision-makers) constitutes the secondary objective. KRIP was selected as case study because it is one of the most successful irrigation project in Nigeria.

4.2 Materials and Methods

4.2.1 Study area

KRIP was established by Kano state government in 1970, with the aim of developing over 62,000 ha of agricultural land for crop production by irrigation using water from Tiga Dam that impounds Kano River. The project is located about 35 km south of Kano City between longitudes 8° 30’ and 9 °40’ E and latitudes 11° 30’ and 12° 03’ N, specifically in Bunkure, Kura and Garun Malam local government areas with project office at Kura (Figure 14). The estimated size of the irrigated land varies according to different research groups; 13,400 ha (Goes, 2002; Simon, 1997) to 19,107 ha (Barbier, 2003) and recently to 22,000 ha (Sangari, 2006). The phase I of the project commenced operation in 1976 after it was formally taken over by the Hadejia-Jama-are River Basin Development Authority (HJRBDA) and Phase II is in the pipeline. The existing scheme includes storage and diversion dam; night reservoirs; main canals with upstream water control; lateral and sub-lateral canals and drainage systems. Water from Tiga dam is discharged into the main irrigation canal having main outlet capacity of 56 m^3s^{-1} and through Ruwan Kanya Reservoir (surface area of 1,500 ha and 33 x 10^6 m^3) it enters the project area at Rano off-take, then is subdivided between west and east branch canal. Water spills into Kano River from main irrigation canal through by-pass outlets. There are also lower level small outlets that discharge directly to Kano River. Water flows from the branch canals into lateral and distribution canals which then supply the irrigation sectors through field channels (Simon, 1997). Ruwan Kanya Reservoir was considered the most suitable alternative instead of having a link canal section that follows the contours around the valley perimeter. The irrigated area is divided into 49 sectors of which 38 are irrigated and 11 sectors are yet to be completed. KRIP infrastructures are generally in fairly good condition, such as the main canals, farm outlet structures and hydro-mechanical equipment. The main drainage systems are eroded in some places but are operational. Vegetation like Typha grass grows in branch canals, lateral canals and distribution canals. In several sections, canals are exposed to erosion and silt deposition was also observed in many lined canals. Water is supplied during dry months from November – March coinciding with peak demand of irrigation (Simon, 1997). Table 12 gives basic meteorological data at Kano River basin as obtained from Nigerian Meteorological Agency (NIMET). The soil around the adjacent farmlands in KRIP was found to be predominantly loamy sands (Sobowale et al., 2014).

As stated in the previous chapter, rice is the common crop grown during wet seasons whereas wheat and tomato are common during dry seasons. Actual crop water requirement is not the guiding principle for the operation of KRIP but rather is based on continuous water supply through main canal to the irrigated areas. Despite significant increases in water demand, it is essentially a supply-based system. Hence, it cannot accommodate changing water demands during the crop season. The period farmers apply water depends on dryness of crops and soils, and in some areas based on recommended day's interval. For instance, Yakasai at Kosawa area are allocated water on every Thursday and Saturday. With regards to water fee, farmers pay ₦10, 000 (US$28)[1] per hectare per season to HJRBDA.

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[1] 1 USD ($) = 360 Naira (₦) at the date of 28th March, 2017

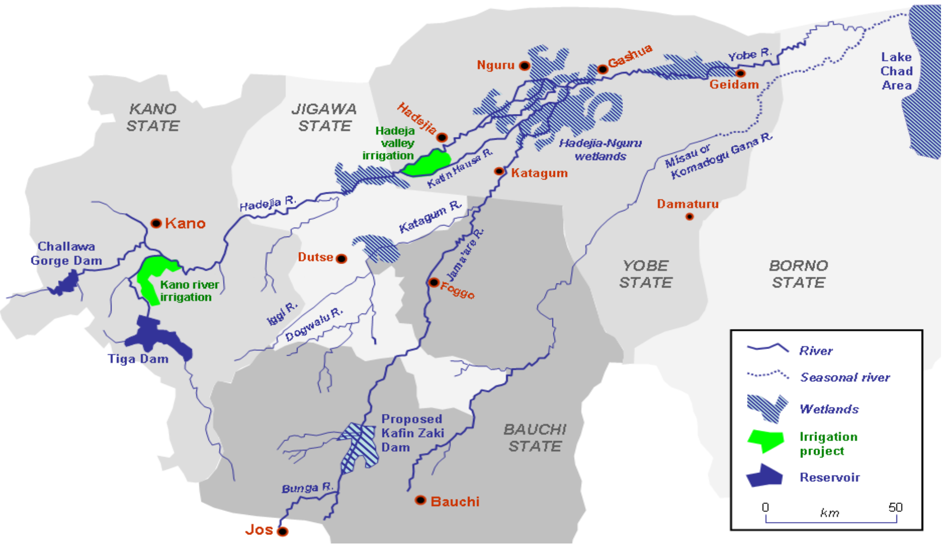


Figure 14 Kano River irrigation project in Kano River basin

Table 12 Meteorological data at Kano River basin (1998)

Month	**Parameter**				
	Average temp. (°C)	**Rainfall (mm)**	**Humidity (%)**	**Wind speed (km/day)**	**Sunshine (hr)**
January	21.4	0	30	152	8.4
February	25.8	0	21	168	5.0
March	26.8	0	14	158	6.2
April	32.8	14.1	43	173	6.4
May	32.6	69.6	55	168	8.2
June	29.2	173.0	67	179	8.5
July	26.9	573.0	78	153	7.9
August	26.3	572.0	82	114	7.5
September	26.9	444.0	79	67	8.4
October	28.0	26.6	56	90	7.7
November	28.0	0	28	113	8.0
December	25	0	25	163	7.1

4.2.2 Sustainable efficiency (Sefficiency)

Sefficiency was used to determine the performance of KRIP. The development of Sefficiency can be categorized into three major levels: macro, meso and micro, which can be found in Haie & Keller (2012, 2014). The details were presented earlier in chapter 3.

4.2.3 Data sources

Crop evapotranspiration requirements were estimated using CROPWAT 8.0 (Swennenhuis 2010). The required meteorological data such as wind speed (u), evaporation, sunshine, maximum and minimum temperature (T_{max} and T_{min}), maximum and minimum relative humidity (RH_{max} and RH_{min}) were recorded in Aminu Kano International Airport (MAKIA) synoptic meteorological station and acquired from Nigerian Meteorological Agency (NIMET). NR_{RES} was calculated using a relation of areas of Tiga dam and RKR. NR_{RES} and spill from RKR to Kano River were subtracted from volume of water supplied to main irrigation canal to get VA. The quantities of the remaining water flow types were measured in a dry-season gauging surveys made just downstream of the dam by Hadejia-Nguru Wetlands Conservation Project (HNWCP) (Goes & Zabudum, 1998). Although the measurements were done in dry season, but the values are normal for KRIP usage. Table 13 presents the data of the dry-season flows according to Figure 15.

Table 13 Dry-season flows in the Hadejia River

Site	Q, ha-m/day
Irrigation canal to Ruwan Kanya Reservoir	169.3
Spill from Ruwan Kanya reservoir to Kano River (SP)	23.3
Outflow from KRIP to Hadejia River (RF)	67.4
Water usage by KRIP and evaporation in RKR (NR_{RES} + VA)	78.6
Kano River near Bagauda Dam, downstream	82.9
Smaller Tiga outlets and By-pass outlet from irrigation canal (BO+SO)	59.6
Inflow to Ruwan Kanya Reservoir (iRKR)	109.7

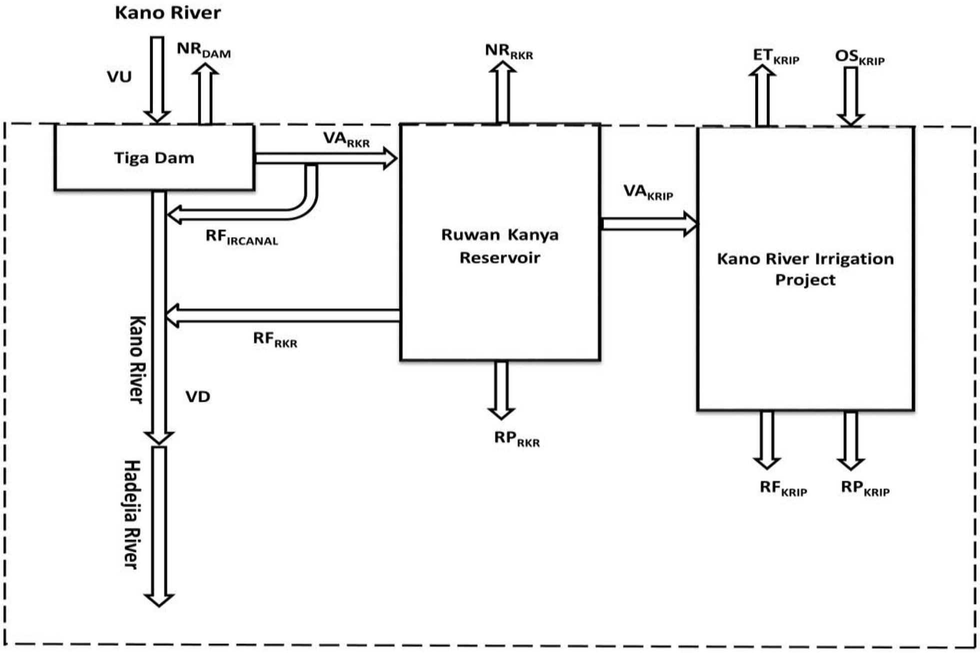


Figure 15 Typical schematic of Kano River Irrigation Project

Let us note that VA$_{RKR}$ is Inflow to Ruwan Kanya Reservoir, RF$_{RKR}$ is Spill from Ruwan Kanya Reservoir, RF$_{KRIP}$ is return flow from KRIP, NR$_{DAM}$ is Non-reusable (evaporation) from Tiga dam and NR$_{RES}$ is Non-reusable (evaporation) from Ruwan Kanya Reservoir and by-pass outlets.

The equivalences of the generic I/O and Sefficiency symbols as used in Figure 15 are presented in Table 14. It is worthy of noting that WaPs symbols (nomenclatures) change according to the system under analysis.

Table 14 Mapping of generic I/O with Sefficiency symbols in KRIP

Generic I/O symbols from Figure 13	Sefficiency symbols in Figure 15
I_{DAM}	VU
I_{KR1}	$RF_{IRCANAL}$
I_{KR2}	RF_{RKR}
I_{KR3}	RF_{KRIP}
I_{KRIP1}	VA_{KRIP}
I_{KRIP2}	OS_{KRIP}
I_{RKR}	VA_{RKR}
O_{RKR1}	NR_{RKR}
O_{RKR2}	RP_{RKR}
O_{KRIP1}	ET_{KRIP}
O_{KRIP2}	RP_{KRIP}
O_{DAM1}	NR_{DAM}
O_{KR5}	VD

Quality weights were assigned considering previous studies in the basin, such as, Goes (2005). To gather management's and farmers' perception on beneficial use of water (beneficial weights), a sample of 45 farmers and 5 from management sides were selected through stratified random sampling and interviewed in March – April 2016. The sample covered the head, middle and tail-end sections of KRIP. Interviews were also conducted with other stakeholders such as water users (non-farmers) and consultants. Besides beneficial weights, questions during the interviews pertained to the management of water resources by HJRBDA and farmers' satisfaction and perception on water availability and allocation to different users. Figure 16 shows the percentage of the principal stakeholders that participated in the survey. The respondents assigned different weight values to each of the variables based on their experiences, knowledge and perception. Wb_{VA}, Wb_{OS}, Wb_{RP} and Wb_{RF} were then computed using arithmetic mean for each principal stakeholder.

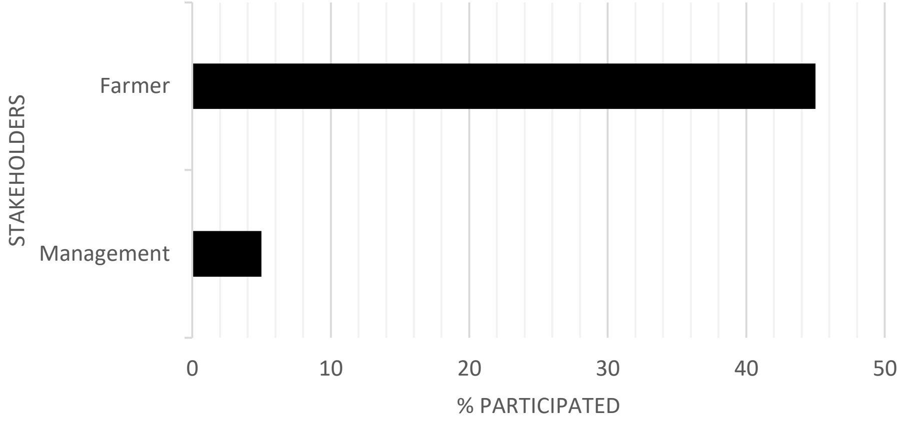


Figure 16 Percentage of stakeholders participated in the survey

4.3 Application

This section discusses the application of Sefficiency in KRIP highlighting different water paths and their quality and beneficial weights as found in the system. Sefficiency is based on law of conservation of mass, hence it is imperative (prerequisite) to have water balance at each junction within the system. Practically, this means that the total outflow should be, say, within five percent of total inflow, because anywhere, including in Nigeria, the accuracy of most of the data has some level of uncertainty. The assessment period was taken as the growing season between the date of sowing and the date of harvest and it is assumed that change of water storage in Tiga dam and RKR are negligible relative to other annual flows within that period.

Using Figure 15, the following two balance equations should be satisfied (equations 8 and 9).

Meso (i.e. KRIP):

$$\boldsymbol{VA_{KRIP} + OS_{KRIP} = ET_{KRIP} + RP_{KRIP} + RF_{KRIP}} \qquad \textbf{(8)}$$

Ruwan Kanya Reservoir (RKR):

$$\boldsymbol{VA_{RKR} = VA_{KRIP} + NR_{RKR} + RP_{RKR} + RF_{KRIP}} \quad \textbf{(9)}$$

Inflow to Ruwan Kanya Reservoir (VA_{RKR}) is the volume supplied to main irrigation canal less smaller Tiga and by-pass outlet from irrigation canal (BO+SO) (refer to Table 13).

Table 15 gives the summary of all KRIP WaPs and their quality and beneficial weights with the details following in the subsequent subsections.

Table 15 WaPs quantity and their quality and beneficial weights of KRIP

	VA_{KRIP}	**ET_{KRIP}**	**RF_{KRIP}**	**RP_{KRIP}**	**OS_{KRIP}**
Quantity (Mm^3)	206	86	101	32	21
W_q	1	1	0.8	0.8	1
W_b Farmer	1	0.85	0.4	0.3	0.1
W_b Management	1	0.85	0.85	0.9	1

4.3.1 Why 22,000 ha is considered as the total size of KRIP

Initially, 335 Mm^3 was designated for irrigating 22,000 ha in KRIP, but now only 15,000 ha is being irrigated by that quantity (Lekan Oyebande & Chiroma, 2003). The higher demand is explained by changes in cropping pattern (rice irrigation instead of wheat) and excessive losses in the secondary and tertiary irrigation channels (Goes, 2005; Oyebande & Chiroma, 2003; Simon, 1997) through water theft. Recently, actual irrigation water requirements, for a full development of KRIP, was estimated by HaskoningDHV (2015) to be 381Mm^3. However, plots engaging in informal irrigation outside of KRIP sectors were observed during the field survey along the second section of the main canal. Mobile pump sets were used to abstract water to these plots initially meant for KRIP (Figure 17a and 17b).

HaskoningDHV (2015) observed that private gravity sector turns out (90 ha) for irrigation was built close to Rano cross regulator, on the left bank of the canal. The area is still being developed and is more extensive than each of the ten smallest sectors in KRIP. A total of the informal irrigation in and around the KRIP zones was estimated at 3,000 ha. This is approximately 15 percent of the total area of KRIP.

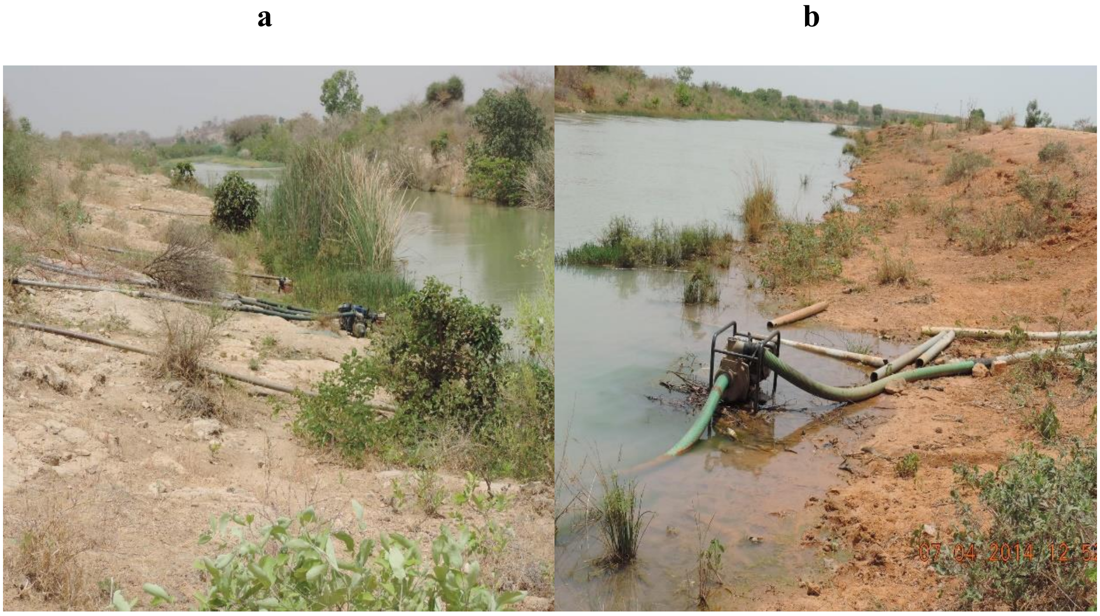


Figure 17 (a) and (b) Informal irrigation of plots outside KRIP sectors

4.3.2 Applied water to KRIP (VA)

Water supplied to main irrigation canal from Tiga dam and spills from RKR to Kano River (RF_{RKR}) was measured to be 25,400 ha-m and 3,500 ha-m, respectively. NR_{RKR} was calculated to be 1,320 ha-m. Thus, VA is approximately 20,580 ha-m (per growing season). W_{qVA} is assigned 1 because the applied water was considered suitable for irrigation. In addition, previous studies have shown that no accumulation of salts was observed and therefore leaching requirement is negligible (Goes, 2005). For the beneficial weight, Wb_{VA} for farmers and management were both estimated to be 1.

4.3.3 Return flow from KRIP (RF_{KRIP})

Maraga is a local name for drainage that carries return flows from irrigated fields to Kano River. A volume of 10,110 ha-m was measured to be the outflow. RF contains chemicals (fertilizers, insecticides, and herbicides) that render the water polluted to some extent, although the degree of pollution may appear not harmful to the farmers. It may even contain emerging pollutants that are toxic and carcinogenic. However, RF_{KRIP} is re-used by farmers downstream (for example around *Gundutse*). Hence, W_{qRF} was assigned 0.8. Furthermore, Wb_{RF} for farmers and management were determined to be 0.4 and 0.85 respectively.

4.3.4 Potential return (RP)

RP was considered to be the water infiltrating soil after water application to be stored as groundwater. Mean annual groundwater recharge was estimated as 390 mm in the study area (Oyebande, 2001). Based on that, RP_{KRIP} is 3,230 ha-m. Although some concerns arise on the quality of wells around the area for drinking water, but as far as irrigation is concerned the water quality is suitable as farmers use groundwater on farms outside the reach of the scheme or where the canals are blocked due to lack of maintenance. Therefore, W_{qRP} was assigned to be 0.8. In addition, Wb_{RP} for farmers and management were determined to be 0.3 and 0.9 respectively.

4.3.5 Actual evapotranspiration (ET_c)

Potential evapotranspiration (ET_o) was calculated to be 8,800 ha-m (5.23 $mmday^{-1}$). This compares well to what Duru (1984) proposed under Nigerian conditions. Actual evapotranspiration (ET_c) was then computed to be 8,630 ha-m adopting FAO-56 approach (Allen, Pereira, Raes, & Smith, 1998) as described in chapter 3. Although food production is the most crucial part of beneficial weight attached to ET, but Wb_{ET} was set to 0.85. It is less than one due to the effects of Typha grass and other weeds present. Consequently, the weight suffers due to non-beneficial ET consumption by

15%. Besides, Wb_{ET} may be reduced if the agricultural system consumes energy in delivering water to plants as may be the case in some places where generators are used to lift water to farms. For the quality weight, W_{qET} was set to be 1. Perhaps the purest water one could get is precipitated water, or evaporated from soil surface or transpired from the stoma of leaves.

4.3.6 Other sources from groundwater (OS)

Although Tiga dam is the main source of water supply in KRIP, the possibility of having other sources in some areas would not be overruled, however, minimal. Some fields that water does not reach due to lack of maintenance of the canals use groundwater (tube wells). Hence, OS_{KRIP} was assumed to be 10% of VA i.e. 2,060 ha-m taking into account slack variable, and W_{qOS} was assigned 1. Also, Wb_{OS} for farmers and management were assigned 0.1 and 1 respectively. A slack variable in the linear programming model is a coefficient that adjusts inputs and outputs.

4.4 Results and Discussion

Meso-efficiency analysis was applied in this study. It considers the impact of KRIP on downstream users, including Kano River (environmental flows). In other words, it includes return flows in the corresponding calculation. Return flows increases the efficiency of WUS, for example, irrigation efficiency of individual districts in Nile river basin was low at around 30% but re-used of return flows downstream raised the overall basin efficiency to around 80% (Qureshi et al., 2011). Figure 18 shows the overall results and the subsequent sections make some comments. In general, management efficiencies are higher than the farmers mostly due to the importance of return flows to managers. Before continuing, let us become clear about terminologies: full inflow Meso-efficiency ($iMesoE_s$) gives the percentage of total useful inflow that is useful outflow, whereas consumptive Meso-efficiency ($cMesoE_s$) provides the percentage of effective consumption that is useful consumption. Quantitative Meso-efficiency ($MesoE_b$) does not consider water quality (in other word assuming quality weight of water to be 1). Consequently, the word “useful” can be replaced by “beneficial”, e.g., useful inflow can be said beneficial inflow.

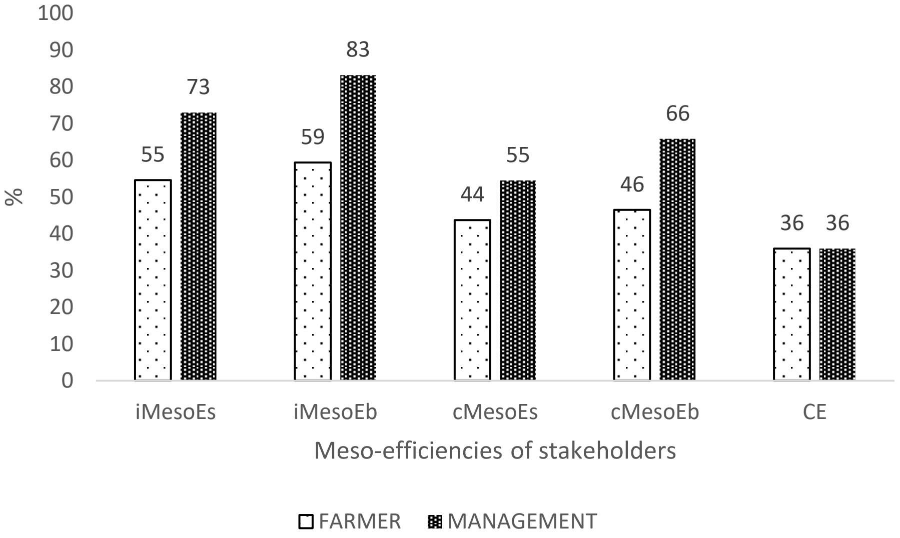


Figure 18 Meso-efficiencies based on stakeholders’ perception

Note: $iMesoE_s$ = inflow Meso-efficiency considering quality; $cMesoE_s$ = consumptive Meso-efficiency considering quality; $iMesoE_b$ = inflow Meso-efficiency without considering quality; $cMesoE_b$ = consumptive Meso-efficiency without considering quality; CE = Classical efficiency

4.4.1 Performance efficiency based on management perspective

The iMesoE values are more than 73%, hence showing a good performance, but still in need of improvement. The cMesoE values are low, particularly the $cMesoE_s$ (=55%), which needs special attention. Results derived show that $iMesoE_s$ is 73% and $cMesoE_s$ is 55%, whereas $iMesoE_b$ and $cMesoE_b$ are found to be 83% and 66% respectively. High differences exist between the efficiencies (see Figure 18). The difference between $cMesoE_s$ and $cMesoE_b$ of 11 pp (percentage points) shows that efficiencies considering water quality is much lower than considering water to be good (i.e. considering water quality to be 1), indicating that pollution increases effective consumption which in turn decreases efficiency. Excessive use of chemicals (fertilizers, herbicides and pesticides) lead to this pollution, which needs to be controlled to increase the performance of the system. Moreover, $iMesoE_s$ and $iMesoE_b$ are functioning at good efficiencies although having significant difference of 10 pp. $iMesoE_b$ is higher and as far as water is concerned KRIP has relatively better efficiency without considering water quality. Alternatively, it can be seen that the useful outflow (numerator of MesoE) decreases more than the useful inflow (denominator) if pollution is included in efficiency calculations. This demonstrates that KRIP is somewhat good in releasing water to downstream users which is beneficial to them and to environmental flows. It also contributes to groundwater recharge (RP) which is highly desired for downstream wells.

Significant difference of 17 pp exists between $iMesoE_b$ and $cMesoE_b$. The relative consumption of beneficial and non-beneficial parts of ET_o from the system are very important since both efficiencies do not consider water quality. The crucial way through which water is lost is by evaporation, which is the undesired part of evapotranspiration in any agricultural system including KRIP. This is possible because the crops were at the initial stages of growth with mostly evaporation, low transpiration, and consequently lower water consumption (ET_o). Likewise, $iMesoE_s$ and $cMesoE_s$ have a difference of 18 pp, approximately the same as their corresponding $MesoE_b$, basically due to evaporation. $iMesoE_s$ and $cMesoE_b$ have a difference of 7 pp because of the impact of pollution and that useful consumption relative to useful return is small, which is an interesting result from the management perspective due to the importance of useful returns.

4.4.2 Performance efficiency based on farmers perspective

According to farmer's perception, iMesoE and cMesoE values are very low mostly due to the assertion that return flows have no beneficial value (please, refer to W_b values in Table 15). Results generated also show that $iMesoE_s$ is 55% and $cMesoE_s$ is 44%, whereas $iMesoE_b$ and $cMesoE_b$ were found to be 59% and 46% respectively (Figure 18). The difference between $cMesoE_s$ and $cMesoE_b$ of 2 pp implied that efficiencies considering water quality or otherwise are almost the same i.e. water coming into KRIP and leaving it have the same quality without any pollution. As such farmers re-use water that drains through drainage systems called *Maraga* for cultivation as observed during field survey, for example, in areas around *Gundutse*. Similarly, $iMesoE_s$ and $iMesoE_b$ differs with 4 pp indicating that efficiency considering water quality or not is practically the same as explained above. In other words, the useful outflow decreases almost the same amount as the useful inflow if pollution is included in efficiency calculations.

There is also high difference between $iMesoE_b$ and $cMesoE_b$ of 13 pp. The relative consumption of beneficial and non-beneficial parts of ET_o from the system are very important since both efficiencies do not consider water quality. The fundamental way through which water is lost is by evaporation, which is the undesired part of evapotranspiration in KRIP. Likewise, $iMesoE_s$ and $cMesoE_s$ have a difference of 11 pp, approximately the same as their corresponding $MesoE_b$, basically due to evaporation losses as some of the farmers especially to those in the upstream and close to distribution canals irrigate daily which result in them over-irrigating. $iMesoE_s$ and $cMesoE_b$ have a difference of 9 pp due to a combination of relatively high return flow (more than 13,000 ha-m) and low pollution impact (farmers' thinking).

4.4.3 Comparison between classical efficiency, management and farmers perspectives

In terms of classical efficiency, KRIP has very low efficiency of 36% for both management and farmers' perspectives because of equal beneficial weights attached to ET and VA (Table 15), and with no leaching requirement considerations (Wq_{VA} value stays at one). Having this in mind, the difference between $MesoE_b$ values and flawed CE varies between 10 and 47 pp indicating rather large discrepancies. As explained in the previous section, this is due to the fact that CE does not consider return flows in its calculations or putting it correctly it considers that return flows have zero beneficial value, i.e., zero beneficial weights. But, of course, this is not correct, for example, the return flows from KRIP emerge downstream and are used by others.

Real water use efficiency, such as, MesoE, increases when part of the irrigation return flow is recycled through the hydrological system (Haie & Keller, 2014; Qureshi et al., 2011). This is also evident in this application because the difference $MesoE_b$ management – CE is much larger than $MesoE_b$ farmers – CE because the former gives much more importance to return flows than the latter.

The results derived also indicated that KRIP management is quite aware of the significance of potential return (RP: groundwater recharge) in the basin. However, farmers believed that potential return is not important as 75% don't use groundwater. This could be the reason behind assigning beneficial weights of 0.3 and 0.1 to potential return (RP) and water from other sources (OS, i.e., groundwater), respectively. They also have different views on return flows (RF). Farmers assigned 0.4 to it because to them water is lost to downstream contrary to the principle of basin water allocation, i.e. water 'loss' upstream may be water gain downstream. On the other hand, both stakeholders attributed that the system loses water mainly through evaporation.

4.5 Conclusions

In this chapter, Sefficiency, a new framework was used to evaluate the performance of Kano River Irrigation Project at meso level looking at it from two different perspectives of major actors in Kano basin. The framework is based on the universal principle of conservation of mass (water balance) and Usefulness Criterion, which advances a new and more complete terminology. Efficiencies using this approach are higher than the classical ones, which lacks comprehensive treatment of an irrigation system. Interesting results emerged due to stakeholder involvement in deriving usefulness criterion of the flow paths that will have a great influence on water policy in Kano river basin.

Two major stakeholders, namely, water managers and farmers, were contacted in order to evaluate their reasoning in relation to the value of water in the basin. The useful consumption relative to effective consumption of farmers is significantly lower than that of management, which shows a higher relative consumptive impact on both KRIP and Kano River. Likewise, the useful outflow per unit of useful inflow decreases relative to that of management because of the significance of useful returns, which is important for Kano city water supply and other downstream users but not to farmers. Looking at management perspective, effective consumption that is useful consumption (cMesoE_s) is lower than relative to beneficial consumption (cMesoE_b) which is an indicative of pollution that increases effective consumption and consequently decreases efficiency. Conversely, beneficial consumption efficiency (cMesoE_b) is lower than inflow efficiency (iMesoE_s) due to a combination of relatively high return flows and the indifference of the farmers in generating pollution by using chemicals such as pesticides, fertilizers and the like. Classical Efficiency (CE), most used in the world, gives much lower values than meso level Sefficiency. CE is flawed and always give very low values and consequently suggests the use of more investment for more equipment. But this initial enthusiasm fades away after years of no real and positive water results.

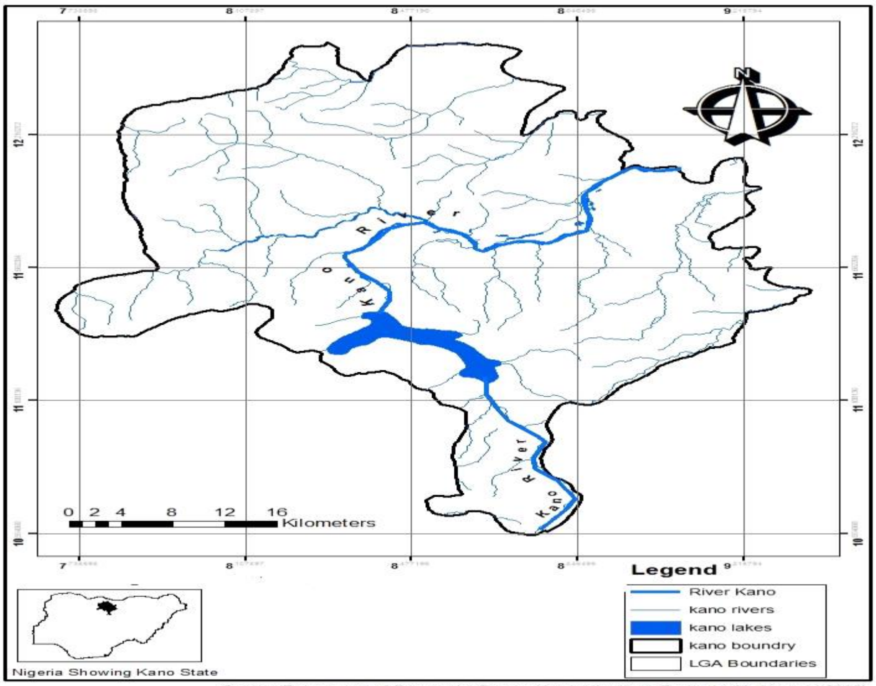
Finally, we suggest the use of the full meso efficiency (MesoEs) of the management perspective for proper policy analysis for Kano basin. This is because management is more holistic and, contrary to the farmers, includes both groundwater and downstream users in defining management practices. The study also recommends using more encompassing technologies such as remote sensing and GIS to derive better data such as the actual irrigated land, flow rates, groundwater recharge, irrigation schedules, etc. Farmers should be educated on the importance of their return flows for basin water allocation and the necessary care for lowering their pollution impact. Lastly, the study should be extended to wet season flows and to include other major water user (Kano city water supply) in the basin.

CHAPTER FIVE

SEFFICIENCY OF KANO RIVER MODEL

5.1 Study area

Kano city is located on the main watershed which separates the two main river basins in the metropolis. The Jakara River basin in the north comprising of Jakara River and its main tributaries – *Gogau, Tukurawa, Gwagwarwa, Rafin Mallam, Tsakama, Cijaki,* and *Getsi*. The Kano River basin (Figure 19) lies to the south of the water divide and is being drained by Rivers Kano and Challawa, and their tributaries – *Watari, 'Yarkuto, Tatsawarki,* and *Salanta* (Bichi & Anyata, 1999).), Kano is the second fastest growing state in Nigeria with a population of approximately 10 million with about 3 million people live in urban Kano (National Population Commission, 2010).



Source: Department of Geography Bayero University, Kano Drawn by M. Ahmed ((2012)

Figure 19 Kano River Basin

5.2 Data sources

The quantities of WaPs were derived from a measurement done by HNWCP (Table 16) (Goes & Zabudum, 1998). Note that inflow to RKR is the volume supplied to the main irrigation canal less smaller Tiga outlets and by-pass outlet from the irrigation canal. The data were compared with the latest available data obtained from various agencies to check for inconsistencies (Figure 20, 21 and 22). Annual evaporation loss for Tiga dam was estimated as 214 Mm^3 (Oyebande, 1995) which is in agreement with 250 Mm^3 (IUCN-HNWCP, 1999). Annual evaporation loss for Kano River was calculated using a relation of Tiga dam and its area (the average surface area at 70% is 107.25 km^2). VA_{KCWS} was obtained from KNSWB who is responsible for water provision in Kano state. The hydrological data were collected from NIMET. Data for average monthly water levels and discharges for Tiga dam and average yearly releases to KRIP was obtained from HJRBDA documents.

Table 16 Dry-season flows in the Hadejia River

Flow component	**Q (Mm^3/year)**
Irrigation canal to Ruwan Kanya Reservoir	618.11
Inflow to Ruwan Kanya Reservoir	400.51
Spill from Ruwan Kanya Reservoir to Kano River	85.15
Outflow from KRIP into Hadejia River	245.98
Water usage by KRIP & evaporation Ruwan Kanya	286.98
Kano River near Bagauda dam, downstream	302.75
Smaller Tiga outlets and by-pass outlet from irrigation canal	217.60
Total releases from Tiga dam	835.70
Releases from Tiga dam in Hadejia River	549.73

Source: (Goes & Zabudum, 1998)

5.3 Option for evaluation

Water supplied by KNSWB is the focus of this study because it is centralized, in other words, manageable compared to other sources such as groundwater, rainwater harvesting, etc. that are somewhat distributed and hence difficult to assess. However, it is worth noting that KNSWB could only provide 50% of the total water demand for Kano metropolis.

5.3.1 Kano River model (M2)

Kano River system emerges from the foothills of the Jos Plateau and flows towards the north until it reaches the confluence with Challawa River at Tamburawa, and together they flow in the eastern direction to formed Hadejia River. Tiga dam controls Kano River, and the reservoir behind it supplies water to KRIP, KCWS and other downstream users (like HVIP) as well as the ecosystems. The main release works at Tiga Dam consists of a single steel pipe culvert running under the dam from an intake chamber. The pipe bifurcates downstream at the toe of the dam. A temporary bulkhead has blocked one pipe which would have discharged into Kano River, and the other pipe rises to feed the canal supplying RKR. The maximum capacity of the canal release valve at full and minimum storage level is 47 and 12 m^3/sec respectively. There is no system in place for the application of release rules from the dam that would match the integrated needs of the downstream users, either regarding time or flows. Nor is there currently adequate flow measurements at critical points in the basin including the dam outlet points and is often operated based on the rule of thumb (Chiroma et al., 2005). The excessive discharges, especially to KCWS, is because a relatively high minimum river flow is required before sufficient water enters the intake works. Figure 20, 21 and 22 provide an overview of Tiga dam average monthly water levels and discharges, and average yearly release to KRIP for various years respectively.

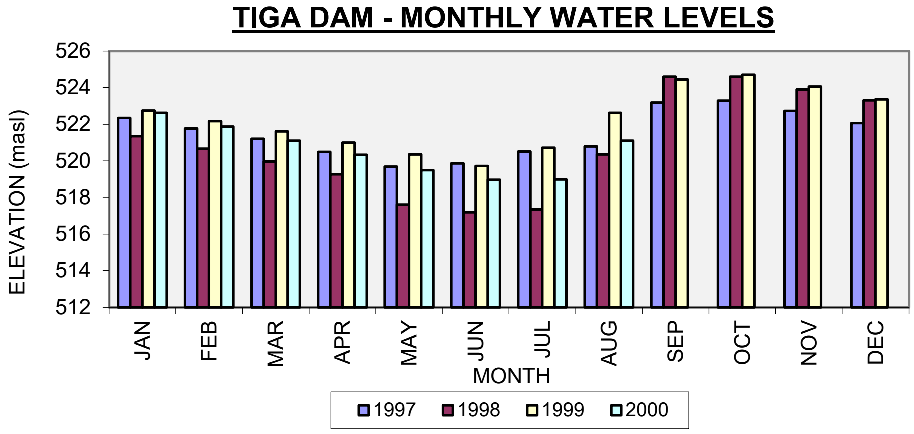


Figure 20 Tiga dam monthly water levels (1997-2000)

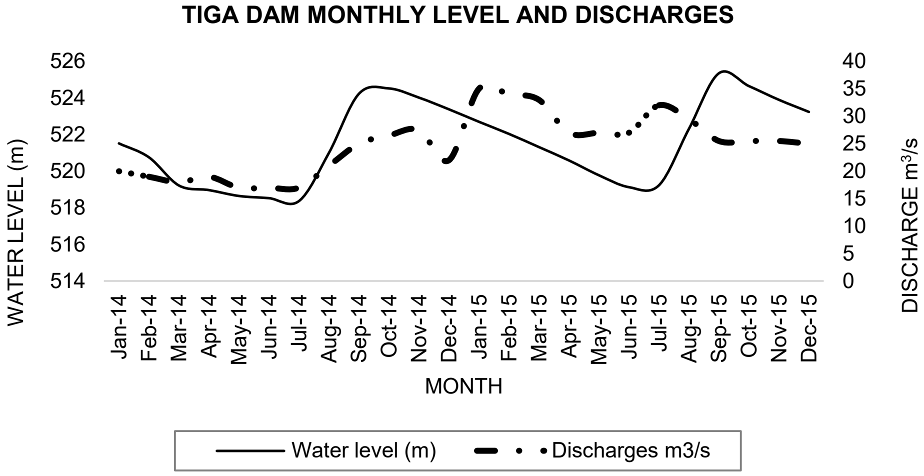


Figure 21 Tiga dam average monthly water level and discharges (2014-2015)

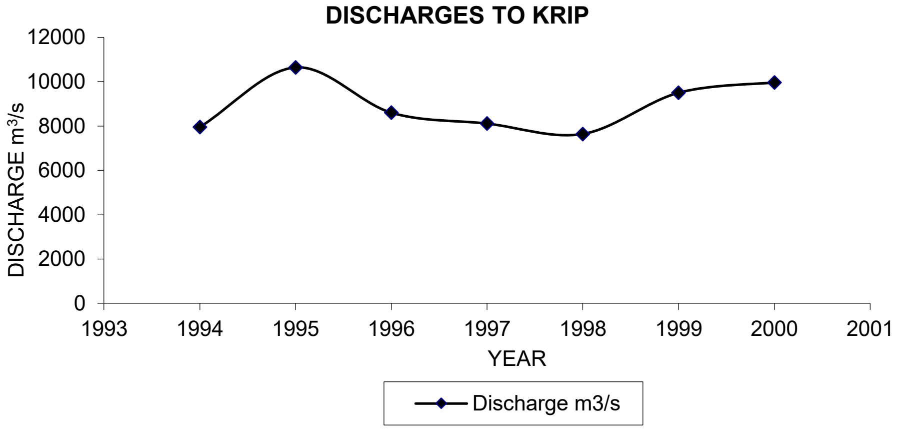


Figure 22 Average yearly discharge to KRIP (1994-2001)

5.3.2 WUS: Boundary, purpose and source of water

In the following analysis, WUS is defined as Kano River including the Tiga dam until downstream just before the point where releases are emptied into Hadejia River, i.e. the confluence of Kano and Challawa Rivers. The primary source of water supply is rainfall impounded in Tiga reservoir, and hence PP over Kano River was also considered. VA and RF are assumed to be the same as VU and VD respectively because the dam and river are part of the WUS. Figure 23 depicts the typical schematic of the WUS under analysis.

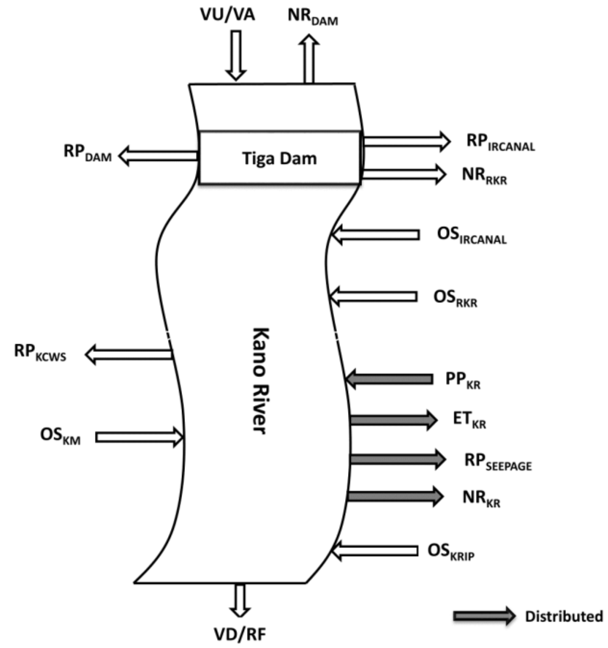


Figure 23 Typical schematic of Kano River

The equivalences of the generic I/O symbols and Sefficiency symbols as used in Figure 23 are presented in Table 17.

It is worth mentioning that WaPs symbols (nomenclatures) change according to the system under analysis, for example, considering River Kano model, O_{RKR3} in Figure 13 becomes RF_{RKR} in Figure 15 while in Figure 23 becomes OS_{RKR}.

Table 17 Mapping of generic I/O with Sefficiency symbols in Kano River model

Generic I/O symbols from Figure 13	**Sefficiency symbols in Figure 23**
I_{DAM}	VU
I_{KR1}	$OS_{IRCANAL}$
I_{KR2}	OS_{RKR}
I_{KR3}	PP_{KR}
I_{KR4}	OS_{KM}
I_{KR5}	OS_{KRIP2}
I_{RKR}	-
I_{KRIP1}	-
I_{KRIP2}	-
O_{DAM1}	NR_{DAM}
O_{DAM2}	$RP_{IRCANAL}$
O_{DAM3}	NR_{RKR}
O_{DAM4}	RP_{DAM}
O_{KR1}	RP_{KCWS}
O_{KR2}	ET_{KR}
O_{KR3}	$RP_{SEEPAGE}$
O_{KR4}	NR_{KR}
O_{KR5}	VD
O_{RKR1}	-
O_{RKR2}	-
O_{KRIP1}	-
O_{KRIP2}	-

5.3.3 Estimates of the quantity values for WaPs

Sefficiency is based on the principle of the conservation of mass. In other words, water balance is one of the central aspects of Sefficiency. Hence water balance at each junction within the system is critical and must be satisfied. Practically, this means that the total outflow should be, say, within five percent of total inflow, because anywhere, including in Nigeria, the accuracy of most of the data has some level of uncertainty.

The timescale of the analysis is taken on a yearly basis during which the change in water storage of Tiga dam is assumed to be negligible relative to other annual flows within that period. It should be mentioned that the water retained within the Kano River is supplemented by local rainfall in the wet season and depleted by evaporation and seepage to groundwater.

The following water balance equation (equation (10)) should be satisfied as depicted in Figure 23.

Kano River:

$$\boldsymbol{VU + PP_{KR} + OS_{IRCANAL} + OS_{KM} + OS_{KRIP2} + OS_{RKR} = ET_{KR} + NR_{DAM} + NR_{KR} + NR_{RKR} + RP_{IRCANAL} + RP_{KCWS} + RP_{SEEPAGE} + RP_{DAM} + VD} \qquad \textbf{(10)}$$

where VU = volume of water upstream of Tiga dam; PP_{KR} = precipitation over Kano River; $OS_{IRCANAL}$ = smaller Tiga outlets and by-pass outlets from irrigation canal; OS_{KM} = wastewater from Kano Metropolis into Kano River; OS_{KRIP2} = return flows from KRIP; OS_{RKR} = spills from RKR to Kano River; ET_{KR} = non-beneficial ET from Kano River; NR_{DAM} = evaporation loss and seepage from Tiga dam; NR_{KR} = evaporation loss from Kano River; NR_{RKR} = consumptive uses by RKR; $RP_{IRCANAL}$ = irrigation canal to RKR; $RP_{SEEPAGE}$ = seepage through Kano River bed; RP_{KCWS} = water applied to KCWS; RP_{DAM} = spills from Tiga dam ; VD = water downstream just before confluence with Challawa River to form Hadejia River

As explained above, VD is the same as RF and VU is the same as VA. It makes sense because the WUS under analysis is part and parcel of the river supplying the water. The following subsections give details of Kano River water flow paths and their quality and beneficial weights.

5.3.3.1 Precipitation (PP_{KR})

The volume of water retained in Kano River is supplemented by local rainfall during the wet season and depleted by evaporation and seepage. Rainfall over the WUS was estimated using Kano River area which has a size of about 30 m wide, which meanders in a 500 m wide floodplain (Neville, Kazaure, & Aliboh, 2005) and extending 62 km downstream of Tiga dam until its confluence with Challawa River (Parkman, 2000). Assuming a direct relationship between the area (using an average width of 90 m) and average annual rainfall of 884 mm, PP was estimated as 5 Mm^3.

5.3.3.2 Evaporation losses from Tiga dam and Kano River (NR_{DAM} and NR_{KR}) and consumptive uses by RKR (NR_{RKR})

The average annual evaporation losses from Tiga reservoir vary from year to year depending on the surface area (and thus the volume of stored water) of the reservoir. Different evaporation losses were estimated in relation to the surface area of Tiga dam. However, average annual evaporation loss (NR_{DAM}) of 214 Mm^3 estimated by Oyebande (1995) was used in this study. The value compares well with 182 Mm^3 at 50% storage (IUCN-HNWCP, 1999). NR_{DAM} is distinct from ET which was calculated separately in the next subsection. Moreover, NR_{KR} was calculated using a relation of NR_{DAM} and its area to be 62 Mm^3. NR_{RKR} is the part of inflow to main irrigation canal consumptively use by Ruwan Kanya Reservoir estimated as 400 Mm^3.

5.3.3.3 Non-beneficial evapotranspiration from Kano River (ET_{KR})

ET is the non-beneficial consumption in Kano River due to the presence of Typha grass and other weeds. ET is part of the water cycle, proceeding regardless of the type of vegetative surfaces that cover the land. In view of that, using $ET_O = 5.23$ mm/day calculated for KRIP, ET was estimated to be 4 Mm^3.

5.3.3.4 Water from other sources (OS)

OS was expanded into four flow paths corresponding to smaller Tiga outlets and by-pass outlets from the irrigation canal, spills from RKR, return flows from KRIP and wastewater flows from Kano Metropolis designated as $OS_{IRCANAL}$, OS_{RKR}, OS_{KRIP} and OS_{KM} respectively. $OS_{IRCANAL}$, OS_{RKR} and OS_{KRIP} were measured to be 218, 85 and 246 Mm^3 respectively.

To find OS_{KM}, domestic wastewater flows was determined from domestic water uses (Mara, 2004):

$$Qww = \frac{kqP}{1000} \tag{11}$$

where Q_{ww} is the wastewater flow, m^3/day; q is the water consumption/uses, l/person/day; P is the population connected to the sewerage system, and k is the 'return factor', the fraction of the water consumed that becomes wastewater (usually 0.8–0.9).

As stated in chapter 3, 70% of drainage of Kano Metropolis is oriented towards northward due to topographic factors into Jakara River and the remaining is assumed to drain into Challawa and Kano Rivers equally. Hence, OS_{KM} is calculated as 5.3 Mm^3 (assuming $k = 0.8$).

5.3.3.5 Potential returns (RP)

RP was expanded into four flow paths, namely, $RP_{IRCANAL}$, RP_{KCWS}, $RP_{SEEPAGE}$ and RP_{DAM}. $RP_{IRCANAL}$ corresponds to that part of the water supplied to irrigation canal measured as 218 Mm^3, which flows back to Kano River. RP_{KCWS} is the amount of water applied to KCWS estimated as 44.2 Mm^3 according to data obtained from planning, research and statistics division of KNSWB. $RP_{SEEPAGE}$ is the volume of seepage through Kano River bed by assuming the groundwater level rise due to river bed recharge of 127 cm (Oyebande, 2001) calculated to be 39 Mm^3. Based on the discussion with the management of HJRBDA, there is a spill from Tiga reservoir into Kano River estimated as 4 Mm^3.

5.3.3.6 Volume downstream (VD) or RF

VD is the amount of water downstream of Kano River precisely just before the confluence of the Kano and Challawa Rivers to form Hadejia River. Practically, VD is the amount of water that is available for downstream users and the minimum flow requirement of the river. It is calculated as 411 Mm^3. Similarly, RF is assumed to be equals to VD following the reason stated earlier.

5.3.3.7 Volume of water upstream (VU) or Applied water (VA)

VU is the total volume of water upstream of Tiga dam estimated at 836 Mm^3. Moreover, VA is the total average annual inflow into Tiga reservoir estimated at 836 Mm^3.

5.3.4 Estimates of WaPs attributes

The water quality weights of $OS_{IRCANAL}$, PP, RP_{DAM}, $RP_{IRCANAL}$, VA and VU are considered basically the same. These flow paths are essentially the same water and hence have the same quality. The quality weights for each of these WaPs (W_{qX} values) are fixed at 1. Similarly, ET_{KR}, NR_{KR} and NR_{DAM} are set at 1 because possibly water evaporated from soil surface or transpired from the stoma of leaves are among the purest one can have. However, the quality of NR_{RKR}, OS_{RKR}, OS_{KRIP2} and OS_{KM} are reduced to 0.8 due to anthropogenic and agricultural activities in Kano city, and around RKR and KRIP. The water quality of RP_{KCWS} is the combination of OS_{RKR} and $OS_{IRCANAL}$. $RP_{SEEPAGE}$, RF and VD are practically the same water and their quality weights are fixed at 0.8.

The beneficial weights of all the flow paths except ET_{KR}, NR_{KR} and NR_{DAM} are fixed to 1, while W_{bNRDAM} and W_{bNRKR} are set to 0.3. The latter weights suffer due to non-beneficial nature of the flow path (i.e., evaporation). Although undesired in the system, evaporation is an essential part of the water cycle. W_{bETKR} is set to 0.15 due to non-beneficial ET consumption (15%) as result of Typha grass and other weeds present in Kano River. Table 18 summarizes the WaP quantities with their corresponding beneficial and quality weights.

Table 18 WaP quantities and their quality and beneficial weights

WaPs	**Quantity (Mm^3)**	**W_{qX}**	**W_{bX}**
VA	836	1	1
$OS_{IRCANAL}$	218	1	1
OS_{KM}	5	0.8	1
OS_{KRIP2}	246	0.8	1
OS_{RKR}	85	0.8	1
PP_{KR}	5	1	1
VU	836	1	1
ET	4	1	0.15
NR_{DAM}	214	1	0.3
NR_{KR}	62	1	0.3
NR_{RKR}	400	0.8	1
RF	411	0.8	1
RP_{DAM}	4	1	1
$RP_{IRCANAL}$	218	1	1
RP_{KCWS}	44	0.8	1
$RP_{SEEPAGE}$	39	0.8	1
VD	411	0.8	1

5.4 Results and Discussion

The following results are showing Sefficiency of Kano River model at different levels and the differences between them. Sefficiency values are assumed to be equal within 2 pp, slightly higher when it is closer to 5 pp and significant or high if more than 5 pp.

5.4.1 Full inflow (iE_s) and consumptive (cE_s) Sefficiency of Kano River

The iE_s is an inflow Sefficiency indicator (i.e., i = 1), which gives the percentage of total useful inflow which is useful outflow. The cE_s (i.e., c = 1) provides the percentage of effective consumption that is useful consumption. The appearance of one of Meso or Macro shows the level of analysis. Generally, the value of Macro efficiency, in this case, is equal to that of Meso efficiency as a result of the equality in values of VU and VA, and that of VD and RF.

Results derived revealed that $iMacroE_s$ is 77% hence showing a good performance, but still in need of improvement and $cMacroE_s$ is 57% is low which needs special attention. On the other hand, $iMacroE_b$ and $cMacroE_b$ are found to be 86 and 71%, respectively. Similarly, $iMesoE_s$ is 77%, and $cMesoE_s$ is 57%. Significant differences exist between the efficiencies (see Figure 24) showing real complexities in the system.

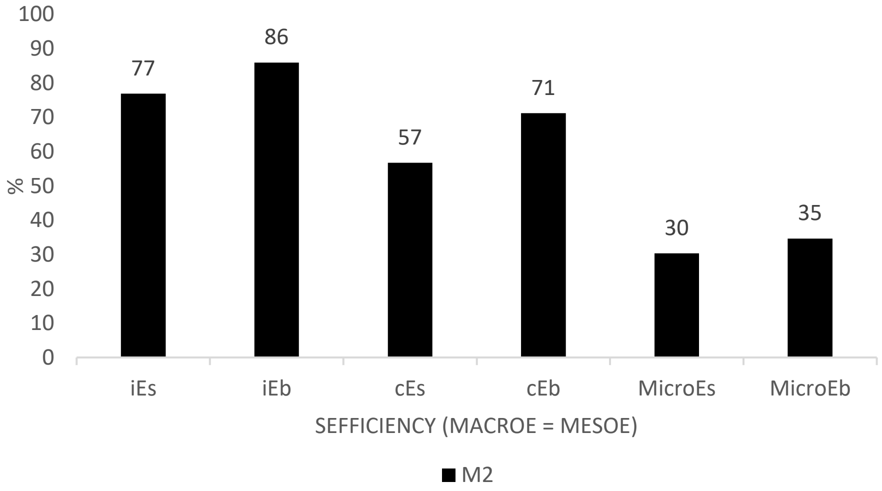


Figure 24 Sefficiency of Kano River model

The results revealed a significant difference of 20 pp between $iMacroE_s$ and $cMacroE_s$ (see Figure 24). This is an indicative of high impacts of pollution in increasing total water consumption of the WUS, which in turn decreases efficiency. The other sources from Kano Metropolis, flood plains (fadama) below Tiga dam and KRIP have significantly higher measures of nitrates and other inorganic fertilizer leachates that increase the effective consumption, which needs to be controlled to enhance the performance of the system. Similarly, the difference between $cMacroE_s$ and $cMacroE_b$ of 14 pp shows that efficiencies considering water quality is lower than considering water to be good (i.e., considering water quality to be 1), indicating that pollution increases effective consumption which in turn decreases efficiency (see Figure 24).

Additionally, $iMacroE_s$ and $iMacroE_b$ are functioning at good efficiencies although having a significant difference of 9 pp. $iMacroE_b$ is higher and as far as water is concerned Kano River has relatively better efficiency without considering water quality. Alternatively, the useful outflow (numerator of MacroE) decreases more than the useful inflow (denominator) if pollution is included in efficiency calculations. This demonstrates that Kano River is somewhat good in releasing water to downstream users which is beneficial to them and to environmental flows. It also plays a significant role in contributing to water allocation to KRIP and KCWS and also to groundwater recharge which is highly desired for downstream wells.

There is also a high difference between $iMacroE_b$ and $cMacroE_b$ of 15 pp. Since both efficiencies do not consider water quality, water consumption is through non-reusable water flow paths (NR) that do not consider quality. Evaporation is the fundamental way through which water is lost, i.e., NR_{DAM} and NR_{KR}. This could be explained more using some of the data presented earlier in Table 20. First, 33% (276Mm^3) of the total average annual volume of water available in Kano River basin is lost through evaporation. Secondly, the amount of water lost through evaporation from the river alone is more than the amount of water abstracted for KCWS. This unhealthy for the basin especially in a semi-arid environment where water is the limiting factor.

The $iMacroE_s$ and $cMacroE_b$ have a difference of 6 pp due to a combination of relatively high return flow (more than 716 Mm^3) and pollution impact.

$MicroE_s$ is very low (30%) suggesting that the WUS itself is not efficient in using its water resources. Perhaps it would be better to try to increase it for the system to become more sustainable. Increasing the useful consumption in terms of decreasing the pollution caused by anthropogenic activities around RKR is the pathway to achieving sustainability.

As stated before that the value of Macro efficiency, in this case, is equal to that of Meso efficiency, the same explanation applies to the Meso level efficiencies.

5.5 Conclusions

Sefficiency, a new framework, was used successfully to evaluate the performance of Kano River at different levels. Generally, Kano River has relatively better efficiency without considering water quality, in other words, the useful outflow (numerator) decreases more than the useful inflow (denominator) if pollution is included in efficiency calculations.

The effective consumption that is useful consumption (cE_s) is lower relative to beneficial consumption (cE_b) which is an indication of pollution that increases effective consumption and consequently decreases efficiency. Conversely, the significant difference between beneficial inflow ($iMacroE_b$ and $iMesoE_b$) and beneficial consumption ($cMacroE_b$ and $cMesoE_b$) indicated that water consumption is through non-reusable water flow paths that do not consider quality, i.e., evaporation. Moreover, beneficial consumption efficiency ($cMacroE_b$ and $cMesoE_b$) is lower than inflow efficiency ($iMacroE_s$ and $iMesoE_s$) due to a combination of relatively high return flow and pollution impact. The study suggests that the WUS itself is not efficient in using its water resources, because $MicroE_s$ value is very low. Increasing the useful consumption in terms of decreasing the pollution caused by anthropogenic activities around RKR is the pathway to achieving sustainability.

From the findings of this study, it is obvious that pollution and evaporation play an important role in the way and manner water is consumed in Kano River. Also, Kano River is somewhat good in releasing water to downstream users which is beneficial to them and to environmental flows. It also plays a significant role in contributing to water allocation to KRIP and KCWS and to groundwater recharge which is highly desired for downstream wells.

CHAPTER SIX
CASE SCENARIOS AND SENSITIVITY ANALYSIS

6.1 Introduction

In this chapter, case scenarios were developed for Kano River basin based on two recent trends and critical drivers of change: (i) population growth; and, (ii) climate change, and their corresponding impact on the performance of water systems under analysis are evaluated. The potential impacts of population growth and climate change in regions where water is scarce, such as semi-arid, and will continue to be, a key concern for the future sustainability of humanity.

There is considerable uncertainty in the impacts of population growth and climate change on WUSs. Dramatic population increase coupled with economic development, and the associated climate change impacts are two primary parts of future plans in Nigeria as depicted in National Water Resources Master Plan 2013 (JICA et al., 2014). Nigeria is currently the seventh-most populous country in the world and its growing speed is fast. It is projected to transcend that of the United States shortly before 2050, at which point it would become the third-most populous country globally (United Nations, Department of Economic and Social Affairs, 2017). Furthermore, climate change and the associated impact may affect the availability and quality of both surface and groundwater, and it may also affect agricultural production and associated ecosystems (Birkenholtz, 2017; FAO, 2015; Fischer et al., 2007; Hall et al., 2017; IPCC, 2014; Kifle Arsiso, Mengistu Tsidu, Stoffberg, & Tadesse, 2017; Niang et al., 2014; Raje & Mujumdar, 2010; Vorosmarty et al., 2000) in most regions of the world including Africa (Faramarzi et al., 2013). Consequently, the two possible factors were identified, quantified and presented in the following sub-sections.

In this context, scenario analysis refers to varying the value of uncertain parameters in order to understand the impact of their uncertainty on the results. Of course, the fundamental issue is to analyse and compare their sensitivity to expected changes in temperature and precipitation due to climate change and increased population growth.

6.2 Population growth

By defining population as a driver of change, we first need to characterize the reference population and the growth rate. The characterization of reference population upon which the future projections were based is presented in the following subsection.

6.2.1 Reference population

Little is available on the population of Kano City outside the national census figures. Hence, the data for this study were obtained from secondary sources, i.e., National Population Commission of Nigeria (NPC). Data is official census figures from the 2006 Nigerian census obtained from National Population Commission (2010) which is the latest census done by Nigerian government. The procedure for the Nigerian 2006 census is described on the NPC website (www.Population.gov.ng).

Kano Metropolis is located at relatively the centre of Kano State between latitudes 11˚52'N and 12˚07'N and longitudes 8˚24'E and 8˚38'E (Figure 25). The population of Kano State is approximately 10 million and metropolitan Kano has a population of 3 million. Kano Metropolis is a conurbation of eight Local Government Areas (LGAs) around the central city, which metamorphosed to form the modern Kano metropolis. The LGAs are Dala, Fagge, Gwale, Kano Municipal, Nassarawa, Tarauni, Kumbotso and Ungogo. Table 19 presents the LGAs in Kano Metropolis along with their corresponding population. It is worthy to note that the Nigerian government structure is developed in three tiers, which are the federal government, state government, and the local government. In that sense, Local Government Area (LGA) is the smallest unit headed by a Chairman.

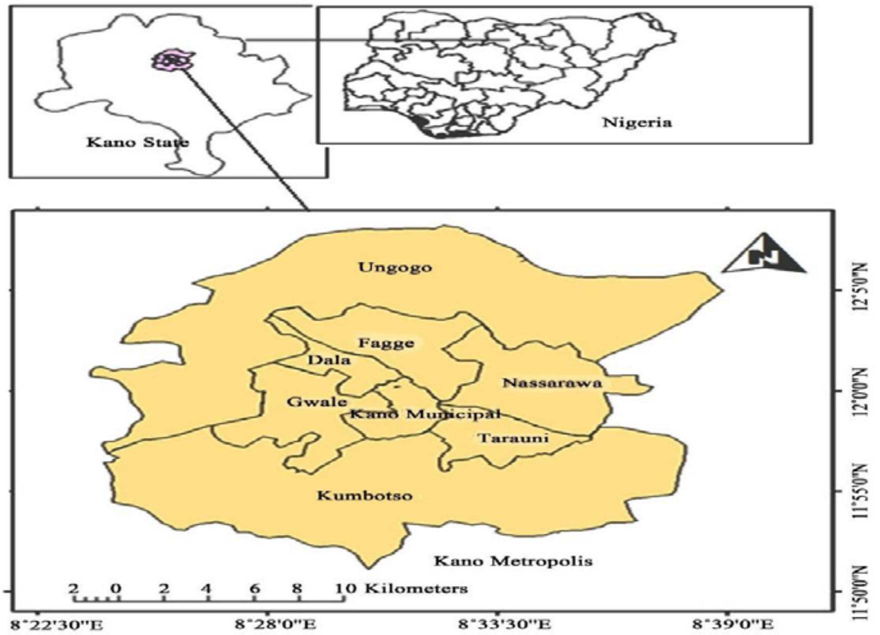


Figure 25 Kano Metropolis

Table 19 LGAs in Kano Metropolis and the associated population as per 2006 census

LGA	Population
Dala	418,759
Fagge	200,095
Gwale	357,827
Kano Municipal	371,243
Kumbotso	294,391
Nassarawa	596,411
Tarauni	221,844
Ungoggo	365,737
Total	**2,826,307**

The population of KRIP as per the 2006 census was estimated at 212,134, i.e., 8% of Kano Metropolis.

6.2.2 Population Growth rate

The growth rate of urban population in Nigeria has been estimated differently in different studies. For example, data from the World Bank of average urban population growth in Nigeria is 4.3% in 2016 (World Bank, 2016). Nevertheless, United Nations

(2016) have used two different growth rates to estimate Kano city's population; 2.2% (2000–2016) and 3.7% (2016-2030). Likewise, National Population Commission (2010) indicated an average growth rate of 3.5% for Kano State (Figure 26). The recent figure of UN is comparable to that of NPC, having an average percentage difference of 3%. Population projection of Kano Metropolis based on the two annual growth rate is presented in the next subsection. Both the rates take into account the historical development, the rate used by previous studies, socio-demographic trends, the rate of Nigerian urban areas, the estimated growth rates of identified socio-demographic categories, and so on (Parkman, 2000). For consistency, NPC rate was used in this study to match with the data from the population census. Besides, the estimated result is correct relative to other projection from UN (refer to Figure 27 in the next subsection).

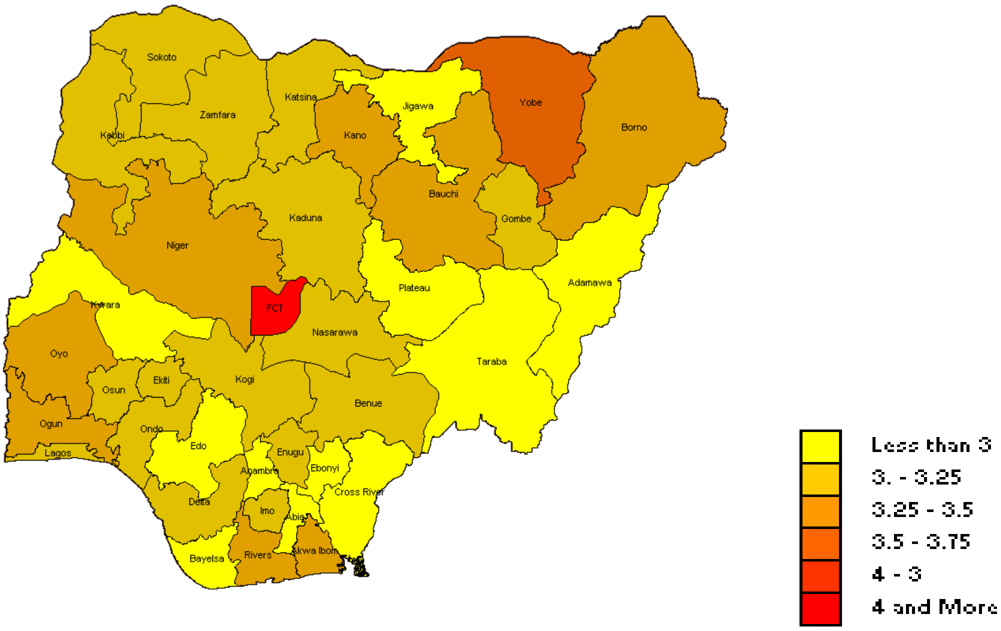


Figure 26 Growth Rate by States (Source: NPC (2010))

6.3 Climate change

Outputs from projections done by Grijsen et al. (2013) from an ensemble of 38 GCM model runs under the median A1B CO_2 emission scenarios is used in this study. The results revealed no upward trend in precipitation until 2050 and by 3% in 2070, while temperature showed a steady increase on average of 2.1°C (8%) by 2050. The implication is an increase of potential evapotranspiration by about 5% for a 2.1°C temperature rise and a similar increase in irrigation requirements (Grijsen et al., 2013). The mean air temperature in the study area 1990 - 2000 was 27°C while rainfall was 884 mm.

6.4 Projections

The primary purpose of producing population projections is to provide an estimate of the future population as a common framework for use in planning, policy formation and decision making in many different fields. In this study, population to be served must be determined for the present and the future to ascertain their water demand. Similarly, climate change projection assesses future vulnerability to climate change. In a nutshell, producing scenarios requires estimates of future population levels and climate change impact.

6.4.1 Population

Projections of future population based on 2006 census population of 2.8 million and growth rate of 3.5% was carried out for 2017, 2025, 2035 and 2050. At this rate, by 2035 the population of Kano Metropolis would almost double the present and tripled by 2050. Figure 27 and 28 show projection of Kano Metropolis based on NPC and UN annual growth rate, and based on NPC annual growth, respectively.

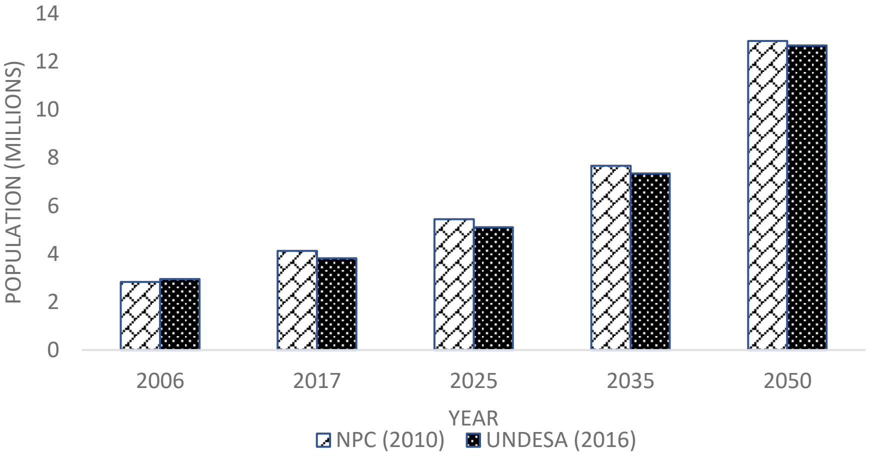


Figure 27 Population projection of Kano Metropolis based on NPC and UN rates

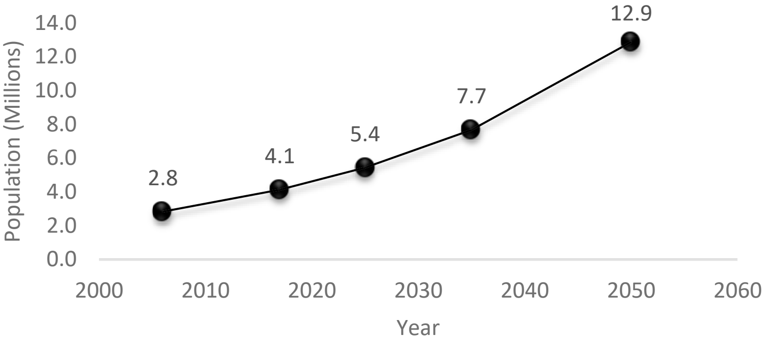


Figure 28 Population projection of Kano Metropolis based on NPC annual growth

6.4.1.1 Urban water demand (KCWS)

Per capita consumption for water was projected using the standard per capita consumption adopted by Parkman (2000) based on different housing types and incomes. It assumed 100% coverage by either house connections or standpipes from KNSWB supply. There is, however, more than 50% of the population that is served directly or indirectly by private boreholes, wells and other sources (Ahmad, 2017). Quite large parts of the city are without pipework or the pipework without any water. Therefore, figures have been adjusted to represent the real number of users better.

It is assumed that consumption per capita will remain stable between 2025 and 2050. In other words, water demand keeps pace with the increase in population only, while per capita demand remains stable. Figures used are already a bit higher than what was found recently in Ahmad & Daura (2017). Instead, to achieve SDGs goal 6, the coverage is expected to increase by 20 pp (from 50% for medium and low-density demand) to 70% and then to 100% in 2025 and 2035. It is a part of the SDGs adopted by Nigeria and other nations to achieve universal and equitable access to safe and affordable drinking water for all by the year 2030. Therefore, water demand for water supply is set to meet 100% of the supply coverage in 2035 and 2050.

Daily average industrial and institutional water uses were calculated as the ratio of 25% and 10% of daily average domestic water uses as adopted in some reports, e.g. JICA et al. (2014). The estimated 'non-revenue' or 'unaccounted for' water is 54% assumed that there is sufficient water supplied to meet it (Parkman, 2000). With repairs and upgrading, a realistic long-term target would be to reduce it to 33% between 2025 and 2050 (JICA et al., 2014).

The abstraction rate for 2015 is based upon data obtained from KNSWB. It is, however, assumed that the volume is the same as the rate abstracted for 2017. The volume abstracted was 44.2 Mm^3 which is 41% of the total Kano city water demand for that year.

Based on the above assumptions, water demand was estimated for 2017 and projected for 2025, 2035 and 2050 and presented in Table 20 and Figure 29. Figure 30 shows the graph of water demand and population in Kano Metropolis according to years projected.

Table 20 Estimated present and projected water demand for Kano city

Consumer Demand	Water uses (lpcd)	2017				2025				2035				2050			
		Total Pop'n (M)	**Coverage (%)**	**Act Pop'n (M)**	**Estimated Demand (Ml/d)**	**Total Pop'n (M)**	**Coverage (%)**	**Act Pop'n (M)**	**Estimated Demand (Ml/d)**	**Total Pop'n (M)**	**Coverage (%)**	**Act Pop'n (M)**	**Estimated Demand (Ml/d)**	**Total Pop'n (M)**	**Coverage (%)**	**Act Pop'n (M)**	**Estimated Demand (Ml/d)**
low density	200	0.12	90	0.11	22.31	0.16	90	0.15	29.37	0.23	100	0.23	46.02	0.39	100	0.39	77.11
medium density	100	0.37	50	0.19	18.59	0.49	70	0.34	34.26	0.69	100	0.62	62.13	1.16	100	1.16	115.67
high density	50	3.64	50	1.82	90.90	4.79	70	3.35	167.51	6.75	100	6.07	303.73	11.31	100	11.31	565.51
Standpipes	20			0.5	10			0.5	10			0.5	10			1	20
Total Domestic		4.13			141.80	5.44		4.34	241.14	7.67		7.43	421.88	12.85		13.85	778
Industries (25% domestic)					35.45				60.3				105.5				195
Institutions (10% domestic)					14.18				24				42				78
Total excluding unaccounted for water					191.43				326				570				1051
% of unaccounted for water					54%				54%				33%				33%
unaccounted for water					295				501				757				1,397

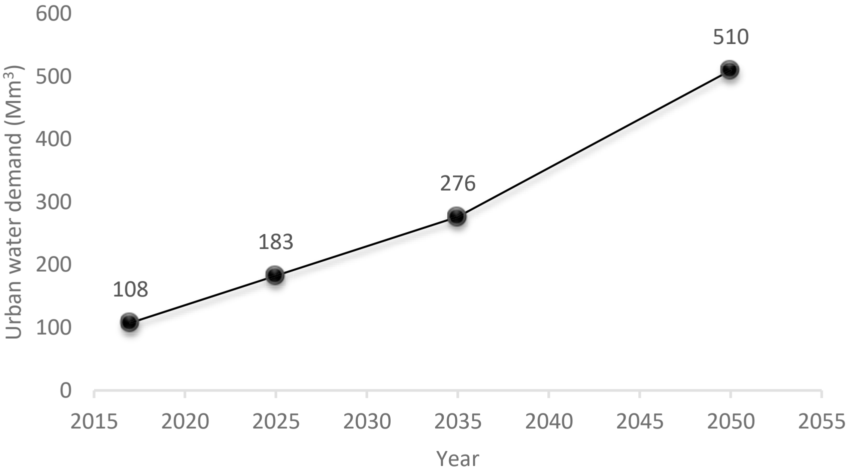


Figure 29 Present and projected water demand for KCWS

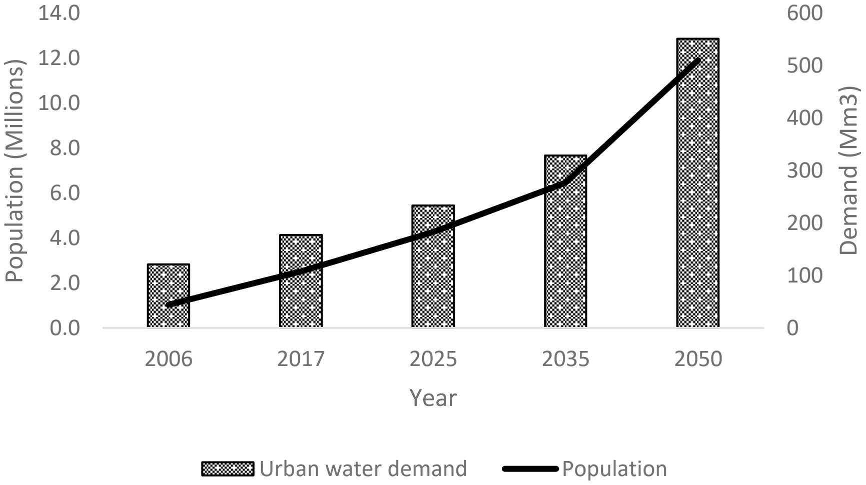


Figure 30 Present and projected water demand and population for Kano Metropolis

6.4.1.2 Irrigation water demand (KRIP)

The present irrigation requirements of KRIP (206 Mm^3) is considered as reference upon which future requirements will be estimated for 2025, 2035 and 2050. The projections are as follows;

a) Present irrigation requirement of 206 Mm^3.

b) A 5% increase in the present irrigation requirements is anticipated by 2035, i.e. 216 Mm^3.

c) By 2050 an increase of 20% over the present irrigation requirements is assumed, i.e. 247 Mm^3.

Details on this are discussed in the next subsection. Figure 31 presents the projected irrigation requirements of KRIP.

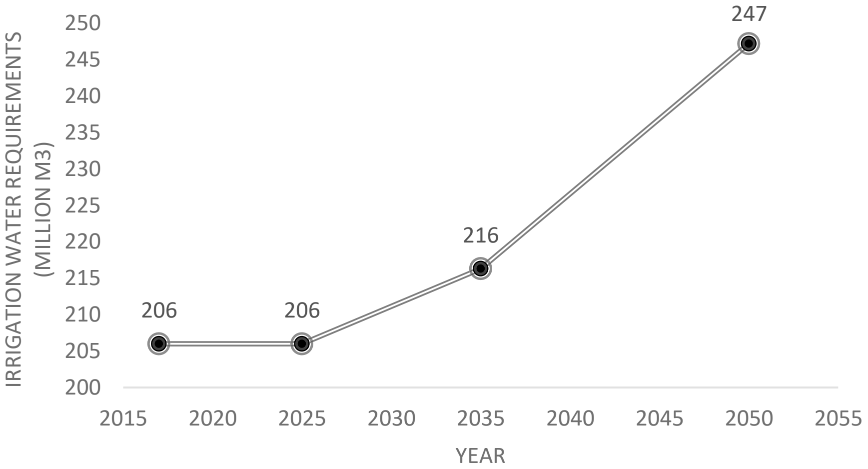


Figure 31 Present and projected water demand for KRIP

6.4.2 Climate change

Table 21 presents the annual rainfall, temperature and evapotranspiration projections for 2017-2050 based on Grijsen et al. (2013) and their percentage changes. In all the projections, the rate of change is uniform and increase is linear (steady). Temperatures show a steady increase of 0.035°C per year and 1.2°C from 2017 to 2050; on average 2.1°C (4% increase) by 2050. Precipitation shows a marginal upward trend by 12.4 mm which is just 1.4% difference by 2050 relative to the reference. Evapotranspiration show a steady increase of 105 mm relative to reference (5.3%) by 2050 (Figure 32).

Table 21 Percentage changes for temperature, precipitation and ET

Year	Temperature Change %	Temperature °C	Precipitation Change %	Precipitation (mm)	ET % Change	ET (mm)
2017, ref	0	27.9	0	884.00	0	1995
2025	1	28.2	0.82	891.29	1.3	2020
2035	2	28.6	1.06	893.35	2.9	2052
2050	4	29.1	1.41	896.45	5.3	2100

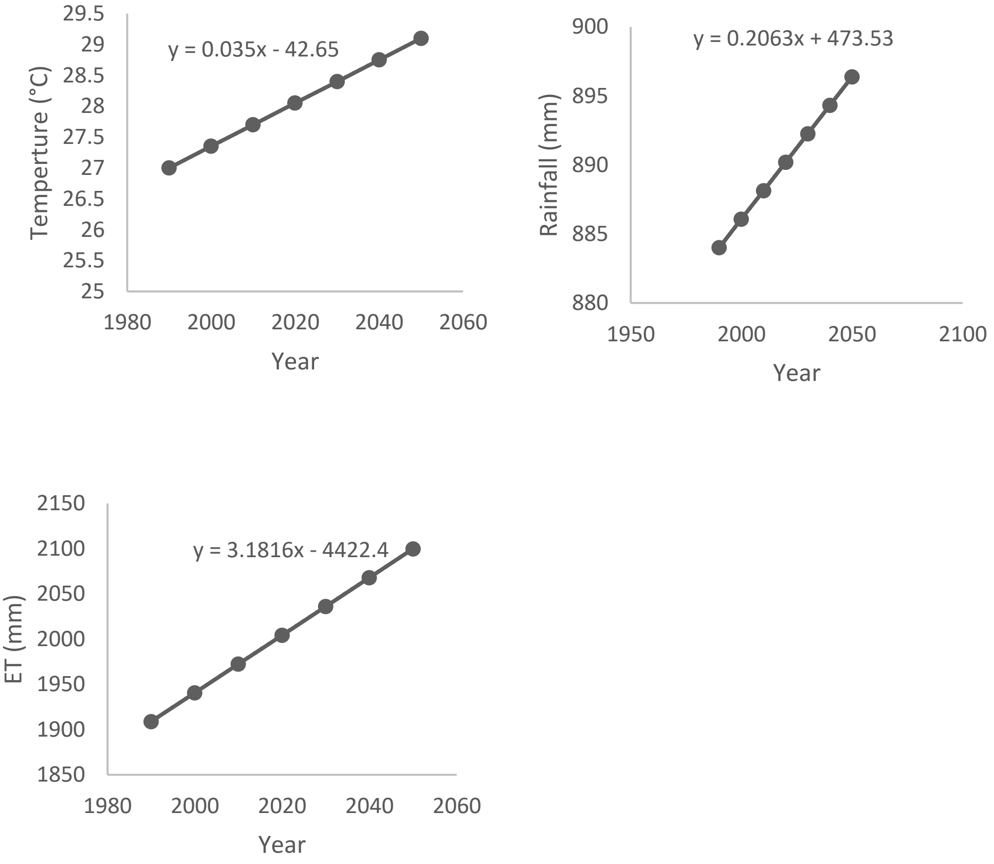


Figure 32 Annual rainfall, temperature and evapotranspiration projections for the 1990-2050

The assessment of impacts of climate change was carried out by incorporating the projected future rainfall, temperature and evapotranspiration data into the various water balance components that are used as an input to Sefficiency model. This resulted in a new set of WaP values as presented in the following subsections.

6.5 Scenarios

In this section, we applied two models designated as M1 and M2 for KRIP and Kano River model, respectively. We also defined 3 sub-models, namely, P, C and B for population, climate change and the duo (population plus climate change) respectively. The appearance of one of P, C or B after M1 or M2 shows the type of scenario. For example, M1P means KRIP model under population impact. These are further expanded taking account the projected year as 1, 2 and 3 for 2025, 2035 and 2050, respectively. For instance, M1P1 refers to KRIP model in 2025. The same procedure was applied to the climate change and the duo (population plus climate change) scenarios. Consequently, we have M1C1 and M1B1, and so on and so forth.

For M1 and M2, a spreadsheet-based application using Microsoft Excel was developed to automatically compute different Sefficiency and generate their graphs. Other files automatically calculate the percentage changes in quantities of different scenarios stating the reasons for the changes and assumptions made.

6.5.1 Population scenarios

This subsection attempts to investigate potential impacts of population growth on the performance of M1 and M2. To do that six scenarios have been developed for Kano River basin; three scenarios for each model, namely, KRIP model (M1P1, M1P2 and M1P3) and Kano River model (M2P1, M2P2 and M2P3).

6.5.1.1 KRIP model (M1P)

Three scenarios are formulated based on the projected population of Kano city and presented in the next subsections. It is worthwhile to mention that irrigation water requirement of KRIP is 206 Mm^3 which accounts for 33% of the total volume of water supplied to main irrigation canal (618 Mm^3) (refer to Table 16 in chapter five).

6.5.1.1.1 WaP quantities, and their quality and beneficial weights for M1P1

As far as volume of water is concerned, no change is expected for M1P1 relative to the reference based on some assumptions. First, the population increase from 2017 to 2025 does not change the volume of water applied to KRIP because according to our surveys, KRIP is already receiving more water than needed. And secondly, cropping patterns do not change. Therefore, irrigation water requirement in 2025 is assumed to be as in 2017 (206 Mm^3), and likewise all other WaPs. WaP quantities for M1P and their percentage changes relative to reference are shown in Table 22 and 23, respectively.

Table 22 WaP quantities for M1P

Quantity (Mm^3)	**M1P0 2017, ref.**	**M1P1 2025**	**M1P2 2035**	**M1P3 2050**
VA_{KRIP}	206	206	216	247
ET_{KRIP}	86	86	91	104
RF_{KRIP}	101	101	106	116
RP_{KRIP}	32	32	34	37
OS_{KRIP1}	21	21	22	22

Note that water balance is the percentage difference relative to IN and OUT, which is within 5% due to the level of uncertainty in the accuracy of the data.

Table 23 Percentage change in WaP quantities for M1P

% Change	M1P0 2017, ref.	M1P1 2025	M1P2 2035	M1P3 2050
VA_{KRIP}	0	0	5	20
ET_{KRIP}	0	0	5	20
RF_{KRIP}	0	0	5	15
RP_{KRIP}	0	0	5	15
OS_{KRIP1}	0	0	5	5

The beneficial weights for all the WaPs in M1P scenarios are basically the same (Table 24). However, the quality weights are affected as presented in Table 25 and their explanation follows.

Table 24 Beneficial weights for M1P

Beneficial weights	M1P0 2017, ref.	M1P1 2025	M1P2 2035	M1P3 2050
VA_{KRIP}	1	1	1	1
ET_{KRIP}	0.85	0.85	0.85	0.85
RF_{KRIP}	0.85	0.85	0.85	0.85
RP_{KRIP}	0.9	0.9	0.9	0.9
OS_{KRIP1}	1	1	1	1

Table 25 Quality weights for M1P

Quality weights	M1P0 2017, ref.	M1P1 2025	M1P2 2035	M1P3 2050
VA_{KRIP}	1	1	1	1
ET_{KRIP}	1	1	1	1
RF_{KRIP}	0.8	0.6	0.4	0.2
RP_{KRIP}	0.8	0.6	0.4	0.2
OS_{KRIP1}	1	1	1	1

6.5.1.1.2 WaP quantities, and their quality and beneficial weights for M1P2

Irrigation water requirement is increased by 5% due to requiring more farmlands for planting because of a moderate increase in population (86% increase relative to the reference). All other WaPs are expected to increase by applying more water, which will, in turn, generate more return flow and groundwater recharge. WaP quantities for M1P2 and their percentage changes relative to reference are shown in Table 22 and Table 23, respectively.

The quality weights of VA_{KRIP}, ET_{KRIP} and OS_{KRIP1} are considered to be basically the same in all scenarios (M1P) because of obvious reasons. However, as farmlands increase, more chemicals (fertilizers, insecticides, and herbicides) are applied causing more pollution. Therefore, the quality weights of RF_{KRIP} and RP_{KRIP} are reduced as shown in Table 25 above. The beneficial weights do not change in all the scenarios (Table 24).

6.5.1.1.3 WaP quantities, and their quality and beneficial weights for M1P3

By 2050, the population of Kano city is projected to more than double relative to the reference. As such much more land is required for planting and consequently much more water needed. However, the construction of hydropower station at Tiga dam by Kano State raises a concern for water availability for KRIP which might limit further expansion of KRIP. Therefore, an increase of 20% is assumed, i.e. 247 Mm^3. Due to that increase, crop water requirements (ET), return flows, groundwater recharge and water from other sources are increased by 20%, 15%, 15% and 5% respectively (refer to Table 22 and 23 above).

There is a decrease in quality weights of RF_{KRIP} and RP_{KRIP} (refer to Table 25) due to increasing pollution as result of applying more chemicals in the additional farmlands.

6.5.1.2 Kano River model (M2P)

For Kano River model (M2P), three scenarios are designed based on the projected water demand for KCWS and irrigation demands as presented in the next subsections.

6.5.1.2.1 WaP quantities, and their quality and beneficial weights for M2P1

In this scenario, 50% of water demand for KCWS will be abstracted from Kano River, i.e., 9% increase relative to 41% in 2017. The remaining will come from other resources like groundwater. Water applied to main irrigation canal is the same in all M2P scenarios, because according to our surveys, is enough to cater for the corresponding increase in farmlands (see Table 22 above). Likewise, water applied to WUS is the same relative to reference because the population increase is relatively small, though water supply coverage increases from 50% in 2017 to 70% to achieve SDGs goal 6. Hence, all other WaPs remain the same as presented in Table 26 and 27.

Table 26 WaP quantities for M2P

Quantity Mm^3	**M2P0 2017, ref.**	**M2P1 2025**	**M2P2 2035**	**M2P3 2050**
VA	836	836	836	836
$OS_{IRCANAL}$	218	218	218	218
OS_{KM}	5	7	10	16
OS_{KRIP2}	246	246	258	283
OS_{RKR}	85	85	85	85
PP_{KR}	5	5	5	5
VU	836	836	836	836
ET	4	4	4	4
NR_{DAM}	214	214	214	214
NR_{KR}	62	62	62	62
NR_{RKR}	400	400	400	400
RF	411	365	305	197
RP_{DAM}	4	4	4	4
$RP_{IRCANAL}$	218	218	218	218
RP_{KCWS}	44	91	166	306
$RP_{SEEPAGE}$	39	39	39	39
VD	411	365	305	197

Table 27 Percentage change in WaP quantities for M2P

% Change	**M2P0**	**M2P1**	**M2P2**	**M2P3**
	2017, ref.	**2025**	**2035**	**2050**
VA	0	0	0	0
$OS_{IRCANAL}$	0	0	0	0
OS_{KM}	0	32	86	211
OS_{KRIP2}	0	0	5	15
OS_{RKR}	0	0	0	0
PP_{KR}	0	0	0	0
VU	0	0	0	0
ET	0	0	0	0
NR_{DAM}	0	0	0	0
NR_{KR}	0	0	0	0
NR_{RKR}	0	0	0	0
RF	0	-11	-26	-52
RP_{DAM}	0	0	0	0
$RP_{IRCANAL}$	0	0	0	0
RP_{KCWS}	0	106	276	592
$RP_{SEEPAGE}$	0	0	0	0
VD	0	-11	-26	-52

The quality weights of VU, VA, $OS_{IRCANAL}$, NR_{DAM}, NR_{KR}, PP_{KR}, RP_{DAM}, $RP_{IRCANAL}$ and ET are considered to be the same in all M2P scenarios. Specifically, VU, VA, $OS_{IRCANAL}$, $RP_{IRCANAL}$ and RP_{DAM} are essentially the same water and set at 1. NR_{DAM}, NR_{KR}, ET and PP are also set at 1, perhaps the purest water one can get is precipitated water, evaporated from soil surface or transpired from the stoma of leaves. However, water from other sources to Kano River is polluted as results of increased anthropogenic and agricultural activities (due to population increase) thereby polluting the water downstream, and consequently affecting the quality weights. Hence, the quality weights of OS_{KM}, OS_{KRIP2}, OS_{RKR}, NR_{RKR}, RP_{KCWS}, RP_{EEPAGE}, RF and VD are affected as shown in Table 28. The beneficial weight of NR_{DAM}, NR_{KR} and ET suffers due to non-beneficial nature of evapotranspiration and evaporation which is undesired in the system (Table 29).

Table 28 Quality weights for M2P

Quality weights	**M2P0** **2017, ref.**	**M2P1** **2025**	**M2P2** **2035**	**M2P3** **2050**
VA	1	1	1	1
$OS_{IRCANAL}$	1	1	1	1
OS_{KM}	0.8	0.6	0.4	0.2
OS_{KRIP2}	0.8	0.6	0.4	0.2
OS_{RKR}	0.8	0.7	0.6	0.5
PP_{KR}	1	1	1	1
VU	1	1	1	1
ET	1	1	1	1
NR_{DAM}	1	1	1	1
NR_{KR}	1	1	1	1
NR_{RKR}	0.8	0.7	0.6	0.5
RF	0.8	0.6	0.4	0.2
RP_{DAM}	1	1	1	1
$RP_{IRCANAL}$	1	1	1	1
RP_{KCWS}	0.8	0.7	0.6	0.5
$RP_{SEEPAGE}$	0.8	0.6	0.4	0.2
VD	0.8	0.6	0.4	0.2

Table 29 Beneficial weights for M2P

Beneficial weights	**M2P0** **2017, ref.**	**M2P1** **2025**	**M2P2** **2035**	**M2P3** **2050**
VA	1	1	1	1
$OS_{IRCANAL}$	1	1	1	1
OS_{KM}	1	1	1	1
OS_{KRIP2}	1	1	1	1
OS_{RKR}	1	1	1	1
PP_{KR}	1	1	1	1
VU	1	1	1	1
ET	0.15	0.15	0.15	0.15
NR_{DAM}	0.3	0.3	0.3	0.3
NR_{KR}	0.3	0.3	0.3	0.3
NR_{RKR}	1	1	1	1
RF	1	1	1	1
RP_{DAM}	1	1	1	1
$RP_{IRCANAL}$	1	1	1	1
RP_{KCWS}	1	1	1	1
$RP_{SEEPAGE}$	1	1	1	1
VD	1	1	1	1

6.5.1.2.2 WaP quantities, and their quality and beneficial weights for M2P2

Upstream flow and applied water to the WUS are not dependant on population change, thus no changes are made to flows that are directly or indirectly dependant on them (Table 26 and 27). To achieve SDGs goal 6, more water is required due to moderate increase in population which will, in turn, leads to more wastewater generation. It may be recalled that 60% of water demand for KCWS in 2035 will be abstracted from Kano River which is expected to cover 100% supply. On the other hand, more return flow is generated as more water is applied to KRIP due to increase in lands. The volume of water downstream decreases due to increase in water abstraction along Kano River, however no regulation or policy that set the value of downstream flows is available.

Due to the importance of environmental flows and downstream users, a minimum of 135 Mm^3 per year is guaranteed as far as this study is concerned.

As said earlier, all the quality weights are considered to be the same with exception of OS_{KM}, OS_{KRIP2}, OS_{RKR}, NR_{RKR}, RP_{KCWS}, RP_{EEPAGE}, RF and VD. Water from other sources to Kano River is polluted thereby polluting the water downstream, and consequently decreasing their quality weights (refer to Table 28). Beneficial weights are the same in all scenarios (Table 29).

6.5.1.2.3 WaP quantities, and their quality and beneficial weights for M2P3

Population change does not influence the upstream flow and applied water to the WUS, hence no changes are made to flows that are directly or indirectly dependant on them (Table 26 and 27). As a result of high population increase in 2050, much more water is required to achieve 100% coverage as set in SDGs goal 6, which will lead to more wastewater generation. Kano River will supply 60% of water demand of KCWS. On the other hand, more return flow is generated as more water is applied to KRIP due to increase in lands. The water downstream decreases due to increase in water abstraction along Kano River, however no regulation or policy that set the value of downstream flows is available. Due to the importance of environmental flows and downstream users, a minimum of 135 Mm^3 per year is guaranteed as far as this study is concerned.

As stated earlier, all the quality weights are considered to be the same with exception of OS_{KM}, OS_{KRIP2}, OS_{RKR}, NR_{RKR}, RP_{KCWS}, RP_{EEPAGE}, RF and VD. Water from other sources to Kano River is polluted thereby polluting the water downstream, and consequently decreasing their quality weights (refer to Table 28). Beneficial weights are the equal in all scenarios (Table 29).

6.5.2 Climate change scenarios

This subsection attempts to investigate potential impacts of future climate change on the performance of M1 and M2. To do that six scenarios have been developed for Kano River basin; three for each model, namely, KRIP model (M1C1, M1C2, and M1C3) and Kano River model (M2C1, M2C2 and M2C3).

6.5.2.1 KRIP model (M1C)

Impact of climate change on the performance of KRIP was investigated by incorporating into WaPs for M1 the projected change in rainfall and temperature with the associated change in ET while keeping population constant. Three scenarios are formulated and presented in the following subsections.

6.5.2.1.1 WaP quantities, and their quality and beneficial weights for M1C1

The impact of increased temperature brings about an increase of 1.3% in potential evapotranspiration and an increase in irrigation requirements by 5% relative to the reference. Moreover, as applied water increases, more return flow and groundwater recharge are generated. However, water from other sources remains the same because KRIP is already getting enough water. WaP quantities for M1C and their percentage changes are shown in Table 30 and 31 respectively.

Table 30 WaP quantities for M1C

Quantity Mm^3	**M1C0**	**M1C1**	**M1C2**	**M1C3**
	2017, ref.	**2025**	**2035**	**2050**
VA_{KRIP}	206	216	216	216
ET_{KRIP}	86	87	89	91
RF_{KRIP}	101	106	106	106
RP_{KRIP}	32	34	34	34
OS_{KRIP}	21	21	21	21

Table 31 Percentage change in WaP quantities for M1C

% Change	**M1C0** **2017, ref.**	**M1C1** **2025**	**M1C2** **2035**	**M1C3** **2050**
VA_{KRIP}	0	5	5	5
ET_{KRIP}	0	1.3	2.9	5.3
RF_{KRIP}	0	5	5	5
RP_{KRIP}	0	5	5	5
OS_{KRIP}	0	0	0	0

The beneficial weights of VA, E_{TKRIP} and OS_{KRIP} are considered to be the equal in all M1C scenarios (Table 32). However, the quality weights of RF_{KRIP} and RP_{KRIP} decrease because when the temperature rises, ET goes up considerably thereby modifying water salinity (Table 33). In other words, quality decreases.

Table 32 Beneficial weights for M1C

Beneficial weights	**M1C0** **2017, ref.**	**M1C1** **2025**	**M1C2** **2035**	**M1C3** **2050**
VA_{KRIP}	1	1	1	1
ET_{KRIP}	0.85	0.85	0.85	0.85
RF_{KRIP}	0.85	0.85	0.85	0.85
RP_{KRIP}	0.9	0.9	0.9	0.9
OS_{KRIP1}	1	1	1	1

Table 33 Quality weights for M1C

Quality weights	**M1C0** **2017, ref.**	**M1C1** **2025**	**M1C2** **2035**	**M1C3** **2050**
VA_{KRIP}	1	1	1	1
ET_{KRIP}	1	1	1	1
RF_{KRIP}	0.8	0.6	0.4	0.2
RP_{KRIP}	0.8	0.6	0.4	0.2
OS_{KRIP1}	1	1	1	1

6.5.2.1.2 WaP quantities, and their quality and beneficial weights for M1C2

In this scenario, rises in temperature due to global warming will cause potential evapotranspiration and irrigation requirements to increase by 2.9% and 5% respectively. Besides, as applied water increases, more return flow and groundwater recharge are generated. However, water from other sources remains unchanged because KRIP is already getting enough water (refer to Table 30 and 31 above).

Due to increase in temperature, more pollution is generated on the farmlands due to salinity thereby decreasing the quality weights of RF_{KRIP} and RP_{KRIP} as shown in Table 33.

6.5.2.1.3 WaP quantities, and their quality and beneficial weights for M1C3

Increase in temperature due to global warming will cause potential evapotranspiration and irrigation requirements to increase by 5.3% and 5% respectively. Besides, as applied water increases, more return flow and groundwater recharge are generated. However, water from other sources remains unchanged because KRIP is already getting enough water (refer to Table 30 and 31 above).

Due to increase in temperature, more pollution is generated on the farmlands thereby decreasing the quality weights of RF_{KRIP} and RP_{KRIP} as shown in Table 33.

6.5.2.2 Kano River model (M2C)

Impact of climate change on the performance of Kano River was investigated by incorporating into WaPs for M2 the projected change in rainfall and temperature with the associated change in ET while keeping population constant. Three scenarios are formulated and presented in the following subsections.

6.5.2.2.1 WaP quantities, and their quality and beneficial weights for M2C1

Temperature rise results in an increase in potential evapotranspiration by 1.3% relative to the reference. The pan evaporation is related to the reference evapotranspiration by an empirically derived pan coefficient (Heydari & Heydari, 2014), in this case by 2.2%. Additionally, rainfall is projected to increase marginally by 0.82%. As evaporation increases, VU and VA decrease and consequently RP_{DAM}, $RP_{IRCANAL}$, $OS_{IRCANAL}$ and RF. Additionally, less water to irrigation canal means fewer spills from small & bye-pass and less water to RKR results in fewer spills from RKR. Less water in Kano River, less groundwater recharge under similar soil conditions. No regulation or policy that set the value of environmental flows and downstream flows, however, due to its importance, a minimum of 135 Mm^3 per year is guaranteed as far as this study is concerned. On the other hand, the influence of global warming on water use is negligible and thus wastewater generation. Similarly, more return flow from KRIP is generated as more applied water is applied. WaPs quantities for M2C and their percentage changes are shown in Table 34 and 35 respectively.

Table 34 WaP quantities of M2C

Quantity **Mm^3**	**M2C0** **2017, ref.**	**M2C1** **2025**	**M2C2** **2035**	**M2C3** **2050**
VA	836	794	773	752
$OS_{IRCANAL}$	218	214	209	203
OS_{KM}	5	5	5	5
OS_{KRIP2}	246	258	258	258
OS_{RKR}	85	83	82	79
PP_{KR}	5	5	5	5
VU	836	794	773	752
ET	4	4	4	4
NR_{DAM}	214	219	225	234
NR_{KR}	62	63	65	68
NR_{RKR}	400	392	384	372
RF	411	382	361	339
RP_{DAM}	4	4	4	4
$RP_{IRCANAL}$	218	214	209	203
RP_{KCWS}	44	44	44	44
$RP_{SEEPAGE}$	39	38	37	36
VD	411	382	361	339

Table 35 Percentage change in WaP quantities for M2

% Change	**M2C0** **2017, ref.**	**M2C1** **2025**	**M2C2** **2035**	**M2C3** **2050**
VA	0	-5	-7.5	-10
$OS_{IRCANAL}$	0	-2	-4	-7
OS_{KM}	0	0	0	0
OS_{KRIP2}	0	5	5	5
OS_{RKR}	0	-2	-4	-7
PP_{KR}	0	0.8	1.1	1.4
VU	0	-5	-7.5	-10
ET	0	1.3	2.9	5.3
NR_{DAM}	0	2.2	5.0	9.2
NR_{KR}	0	2.2	5.0	9.2
NR_{RKR}	0	-2	-4	-7
RF	0	-7	-12	-18
RP_{DAM}	0	-2	-4	-7
$RP_{IRCANAL}$	0	-2	-4	-7
RP_{KCWS}	0	0	0	0
$RP_{SEEPAGE}$	0	-2	-4	-7
VD	0	-7	-12	-18

The quality weights of evaporation and ET are not affected and hence assumed to be the same in all M2C scenarios. However, the qualities of all other flows are reduced due to the decrease in quality of water upstream and the return flow from KRIP further deteriorating it. Table 36 presents the degree of deterioration in the quality weights of the affected flows. Table 37 presents the beneficial weights of M2C.

Table 36 Quality weights for M2C

Quality weights	**M2C0** **2017, ref.**	**M2C1** **2025**	**M2C2** **2035**	**M2C3** **2050**
VA	1	0.9	0.8	0.7
$OS_{IRCANAL}$	1	0.9	0.8	0.7
OS_{KM}	1	0.9	0.8	0.7
OS_{KRIP2}	0.8	0.7	0.6	0.5
OS_{RKR}	1	0.9	0.8	0.7
PP_{KR}	1	1	1	1
VU	1	0.9	0.8	0.7
ET	1	1	1	1
NR_{DAM}	1	1	1	1
NR_{KR}	1	1	1	1
NR_{RKR}	1	0.9	0.8	0.7
RF	0.8	0.6	0.4	0.2
RP_{DAM}	1	0.9	0.8	0.7
$RP_{IRCANAL}$	1	0.9	0.8	0.7
RP_{KCWS}	1	0.9	0.8	0.7
$RP_{SEEPAGE}$	0.8	0.6	0.4	0.2
VD	0.8	0.6	0.4	0.2

Table 37 Beneficial weights for M2C

Beneficial weights	M2P0 2017, ref.	M2P1 2025	M2P2 2035	M2P3 2050
VA	1	1	1	1
$OS_{IRCANAL}$	1	1	1	1
OS_{KM}	1	1	1	1
OS_{KRIP2}	1	1	1	1
OS_{RKR}	1	1	1	1
PP_{KR}	1	1	1	1
VU	1	1	1	1
ET	0.15	0.15	0.15	0.15
NR_{DAM}	0.3	0.3	0.3	0.3
NR_{KR}	0.3	0.3	0.3	0.3
NR_{RKR}	1	1	1	1
RF	1	1	1	1
RP_{DAM}	1	1	1	1
$RP_{IRCANAL}$	1	1	1	1
RP_{KCWS}	1	1	1	1
$RP_{SEEPAGE}$	1	1	1	1
VD	1	1	1	1

6.5.2.2.2 WaP quantities, and their quality and beneficial weights for M2C2

Temperature rise results in an increase in potential evapotranspiration and evaporation by 2.9% and 5% respectively relative to the reference. Also, rainfall is projected to increase by 1.1%. As evaporation increases, VU and VA decrease and consequently RP_{DAM}, $RP_{IRCANAL}$, $OS_{IRCANAL}$ and RF. Additionally, less water to irrigation canal means fewer spills from small & bye-pass and less water to RKR results in fewer spills from RKR. Less water in Kano River, less groundwater recharge under similar soil conditions. No regulation or policy that set the value of environmental flows and downstream flows, however, due to its importance, a minimum of 135 Mm^3 per year is guaranteed as far as this study is concerned. On the other hand, the influence of global warming on water use is negligible and thus wastewater generation. Similarly, more return flow from KRIP is generated as more applied water is applied. WaP quantities for M2C and their percentage changes are shown above in Table 34 and 35 respectively.

The quality weights of evaporation and ET are not affected and therefore considered equal all M2C scenarios. However, the qualities of all other flows are reduced due to the decrease in quality of water upstream and the return flow from KRIP further deteriorating it (refer to Table 36).

6.5.2.2.3 WaP quantities, and their quality and beneficial weights for M2C3

Temperature rise results in an increase in potential evapotranspiration and evaporation by 5.3% and 9.2% respectively relative to the reference. Also, rainfall is projected to increase by 1.4%. As evaporation increases, VU and VA decrease and consequently RP_{DAM}, $RP_{IRCANAL}$, $OS_{IRCANAL}$ and RF. Additionally, less water to irrigation canal means fewer spills from small & bye-pass and less water to RKR results in fewer spills from RKR. Less water in Kano River, less groundwater recharge under same soil conditions. No regulation or policy that set the value of environmental flows and downstream flows as explained above. On the other hand, the influence of global warming on water use is negligible and thus wastewater generation. Similarly, more return flow from KRIP is generated as more applied water is applied. WaP quantities for M2C and their percentage changes are shown above in Table 34 and 35 respectively.

The quality weights of evaporation and ET are not affected and hence ssumed to be identical in all M2C scenarios. However, the qualities of all other flows are reduced due to the decrease in quality of water upstream and the return flow from KRIP further deteriorating it (refer to Table 36).

6.5.3 Population and climate change scenarios

Considering the impacts of population growth and climate change on Kano River concurrently, six scenarios have been developed; three scenarios for each model, namely, KRIP model (M1B1, M1B2 and M1B3) and Kano River model (M2B1, M2B2 and M2B3).

6.5.3.1 KRIP model (M1B)

To investigate the combined impact of climate change and population growth on the performance of KRIP, the projected change in population, rainfall and temperature with associated change in ET were incorporated into WaPs for M1 simultaneously. Practically, the percentage changes of water quantities of M1B equal the sum of percentage changes of water quantities of M1P and M1C. Likewisw, assumptions for changes of M1B equal the sum of the assumptions of M1P and M1C. Three scenarios were formulated and are presented in the following subsections.

6.5.3.1.1 WaP quantities, and their quality and beneficial weights for M1B

The flow quantities of M1B are estimated by adding the percentage changes of water quantities of M1P and M1C. Likewise, the reasons for the changes of the flow quantities of M1B are the combinations of the reasons for M1P and M1C. Table 38 and 39 present WaPs quantities for M1B and their percentage changes respectively.

Table 38 WaP quantities for M1B

Quantity Mm^3	**M1B0 2017, ref.**	**M1B1 2025**	**M1B2 2035**	**M1B3 2050**
VA_{KRIP}	206	216	226	257
ET_{KRIP}	86	87	93	108
RF_{KRIP}	101	106	111	121
RP_{KRIP}	32	34	36	39
OS_{KRIP}	21	21	22	22

Table 39 Percentage change in WaP quantities for M1B

% Change	**M1B0 2017, ref.**	**M1B1 2025**	**M1B2 2035**	**M1B3 2050**
VA_{KRIP}	0	5	10	25
ET_{KRIP}	0	1.3	7.9	25.3
RF_{KRIP}	0	5	10	20
RP_{KRIP}	0	5	10	20
OS_{KRIP}	0	0	5	5

The quality weights of M1B1 scenarios are average of the quality weights of M1P1 and M1C1 scenarios.Table 40 presents the quality weights of M1B.

Table 40 Quality weights for M1B

Quality weights	**M1B0 2017, ref.**	**M1B1 2025**	**M1B2 2035**	**M1B3 2050**
VA_{KRIP}	1	1	1	1
ET_{KRIP}	1	1	1	1
RF_{KRIP}	0.8	0.6	0.5	0.3
RP_{KRIP}	0.8	0.6	0.5	0.3
OS_{KRIP1}	1	1	1	1

The beneficial weights of M1B are the same as in all other scenarios as shown in Table 41.

Table 41 Beneficial weights for M1B

Beneficial weights	**M1B0 2017, ref.**	**M1B1 2025**	**M1B2 2035**	**M1B3 2050**
VA_{KRIP}	1	1	1	1
ET_{KRIP}	0.85	0.85	0.85	0.85
RF_{KRIP}	0.85	0.85	0.85	0.85
RP_{KRIP}	0.9	0.9	0.9	0.9
OS_{KRIP1}	1	1	1	1

6.5.3.2 Kano River model (M2B)

To investigate the combined impact of climate change and population growth on the performance of Kano River, the projected change in population, rainfall and temperature with associated change in ET were incorporated into quantities for M2 simultaneously. Practically, the percentage changes of water quantities of M2B equal the sum of percentage changes of water quantities of M2P and M2C. In the same manner, assumptions for changes of M2B equal the sum of the assumptions of M2P and M2C. Three scenarios were formulated and are presented in the following subsections.

6.5.3.2.1 WaP quantities, and their quality and beneficial weights for M2B

The flow quantities of M2B are estimated by adding the percentage changes of water quantities of M2P and M2C. Likewise, the reasons for the changes of the flow quantities of M2B are the combinations of the reasons for M2P and M2C. Table 42 and 43 present M2B WaPs quantities and their percentage changes respectively.

Table 42 WaP quantities for M2B

Quantity **Mm^3**	**M2B0** **2017, ref.**	**M2B1** **2025**	**M2B2** **2035**	**M2B3** **2050**
VA	836	794	773	752
$OS_{IRCANAL}$	218	214	209	203
OS_{KM}	5	7	10	16
OS_{KRIP2}	246	258	271	295
OS_{RKR}	85	83	82	79
PP_{KR}	5	5	5	5
VU	836	794	773	752
ET	4	4	4	4
NR_{DAM}	214	219	225	234
NR_{KR}	62	63	65	68
NR_{RKR}	400	392	384	372
RF	411	337	255	125
RP_{DAM}	4	4	4	4
$RP_{IRCANAL}$	218	214	209	203
RP_{KCWS}	44	91	166	306
$RP_{SEEPAGE}$	39	38	37	36
VD	411	337	255	125

Table 43 Percentage change in WaP quantities for M2B

% Change	**M2B0** **2017, ref.**	**M2B1** **2025**	**M2B2** **2035**	**M2B3** **2050**
VA	0	-5	-7.5	-10
$OS_{IRCANAL}$	0	-2	-4	-7
OS_{KM}	0	32	86	211
OS_{KRIP2}	0	5	10	20
OS_{RKR}	0	-2	-4	-7
PP_{KR}	0	0.8	1.1	1.4
VU	0	-5	-7.5	-10
ET	0	1.3	2.9	5.3
NR_{DAM}	0	2.2	5.0	9.2
NR_{KR}	0	2.2	5.0	9.2
NR_{RKR}	0	-2	-4	-7
RF	0	-18	-38	-70
RP_{DAM}	0	-2	-4	-7
$RP_{IRCANAL}$	0	-2	-4	-7
RP_{KCWS}	0	106	276	592
$RP_{SEEPAGE}$	0	-2	-4	-7
VD	0	-18	-38	-70

The quality weights for M2B scenarios are average of the quality weights of M2P and M2C scenarios. Table 44 presents the degree of deterioration in the quality weights of the affected flows and Table 45 presents the beneficial weights for M2B.

Table 44 Quality weights for M2B

Quality weights	**M2B0** **2017, ref.**	**M2B1** **2025**	**M2B2** **2035**	**M2B3** **2050**
VA	1	0.95	0.9	0.85
$OS_{IRCANAL}$	1	0.95	0.9	0.85
OS_{KM}	0.9	0.75	0.6	0.45
OS_{KRIP2}	0.8	0.65	0.5	0.35
OS_{RKR}	0.9	0.8	0.7	0.6
PP_{KR}	1	1	1	1
VU	1	0.95	0.9	0.85
ET	1	1	1	1
NR_{DAM}	1	1	1	1
NR_{KR}	1	1	1	1
NR_{RKR}	0.9	0.8	0.7	0.6
RF	0.8	0.6	0.4	0.2
RP_{DAM}	1	0.95	0.9	0.85
$RP_{IRCANAL}$	1	0.95	0.9	0.85
RP_{KCWS}	0.9	0.8	0.7	0.6
$RP_{SEEPAGE}$	0.8	0.6	0.4	0.2
VD	0.8	0.6	0.4	0.2

Table 45 Beneficial weights for M2B

Beneficial weights	**M2B0** **2017, ref.**	**M2B1** **2025**	**M2B2** **2035**	**M2B3** **2050**
VA	1	1	1	1
$OS_{IRCANAL}$	1	1	1	1
OS_{KM}	1	1	1	1
OS_{KRIP2}	1	1	1	1
OS_{RKR}	1	1	1	1
PP_{KR}	1	1	1	1
VU	1	1	1	1
ET	0.15	0.15	0.15	0.15
NR_{DAM}	0.3	0.3	0.3	0.3
NR_{KR}	0.3	0.3	0.3	0.3
NR_{RKR}	1	1	1	1
RF	1	1	1	1
RP_{DAM}	1	1	1	1
$RP_{IRCANAL}$	1	1	1	1
RP_{KCWS}	1	1	1	1
$RP_{SEEPAGE}$	1	1	1	1
VD	1	1	1	1

6.6 Results and Discussion

Results of the systems evaluations with Sefficiency concept were presented in the next subsections, showing the performances of M1 and M2 at different levels and the differences between their scenarios. Also, CE was obtained in all M1 scenarios. The linguistic discussion that follows uses the procedure explained in detail in earlier chapters, according to Haie & Keller (2014) relative to the difference in percentage points. Sefficiency values within 2 pp can be considered equal and significant or high if it is greater than 5 pp. If the difference is closer to 5, the greater is considered slightly higher. In general, the results are complex as one expects for a system with so many variables and parameters. This application shows the following possible results as presented in the following subsections. It is worth mentioning that in all M2 results,

$MacroE_s$ and $MesoE_s$ values are equal. Hence $iMesoE_s$ or $iMacroE_s$ and $cMesoE_s$ or $cMacroE_s$ are represented by iE_s and cE_s respectively. The difference in percentage points between scenarios gives the magnitude of the impact it has on performance. The higher the number, the bigger the impact.

6.6.1 Sefficiency results based on population growth

Results of Sefficiency for the two models based on population scenarios are presented in the next subsection.

6.6.1.1 Sefficiency for M1P

Both inflow and consumptive meso-efficiency ($iMesoE_s$ and $cMesoE_s$) values for M1P1, M1P2 and M1P3 scenarios go down significantly (i.e., greater than 5 pp) compared to M1P0. This suggests that useful outflow per unit of useful inflow decreases, and useful consumption per unit of effective consumption decreases relative to the reference.

The $cMesoE_s$ for M1P0 (55%) shows better performance results of Sefficiency (Figure 33). The highest difference is between M1P0 and M1P3, making the relative consumptive impact of M1P3 on the WUS rather high (Figure 34). The impacts are highest when the applied water (VA) and ET increase both by 20%. This indicates that due to the high increase in population, much more land is required for planting and consequently generating more pollution. Hence, population growth resulted in decreasing the performance of KRIP due to pollution generated because of increased agricultural activities in farmlands. See Figure 34 and Appendix for a difference in percentage points for M1P. For $iMesoE_s$, the difference between inflow efficiency of all the scenarios have the same value, i.e., 10 pp. The useful outflow compared with useful inflow for the WUS and basin is significantly lower (Figure 34).

Even though beneficial weights (W_b) stay the same in all the different scenarios, and quantities change up to 20%, but the quantitative efficiencies (E_b) do not change. In reality, other efficiency terms that do not consider quality in their equations and show the same efficiency although quality changes (like CE, see Figure 33). In other words, although the quantities change, their fractions remain relatively the same. In these scenarios, water quality has an influence on the performance of KRIP under the influence of population growth.

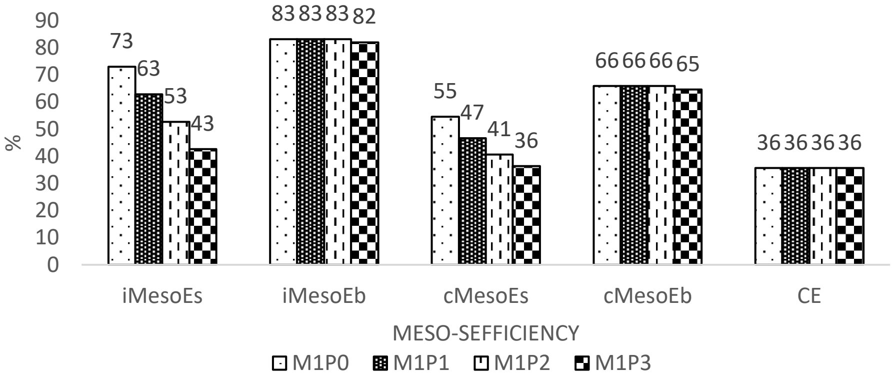


Figure 33 Sefficiency for M1P

Another interesting result is the famous CE that gives the worst efficiency for all the scenarios. For M1, very low values of CE were obtained in all the scenarios. This is because CE does not consider issues such as water reuse (return flows), distinction between total water use and water consumption, effect of use location in an irrigated district or a basin and water quality. However, these issues are particularly important for water management especially in a context of water scarcity. For example, efficiency increases when part of the irrigation return flow is recycled through the hydrological system.

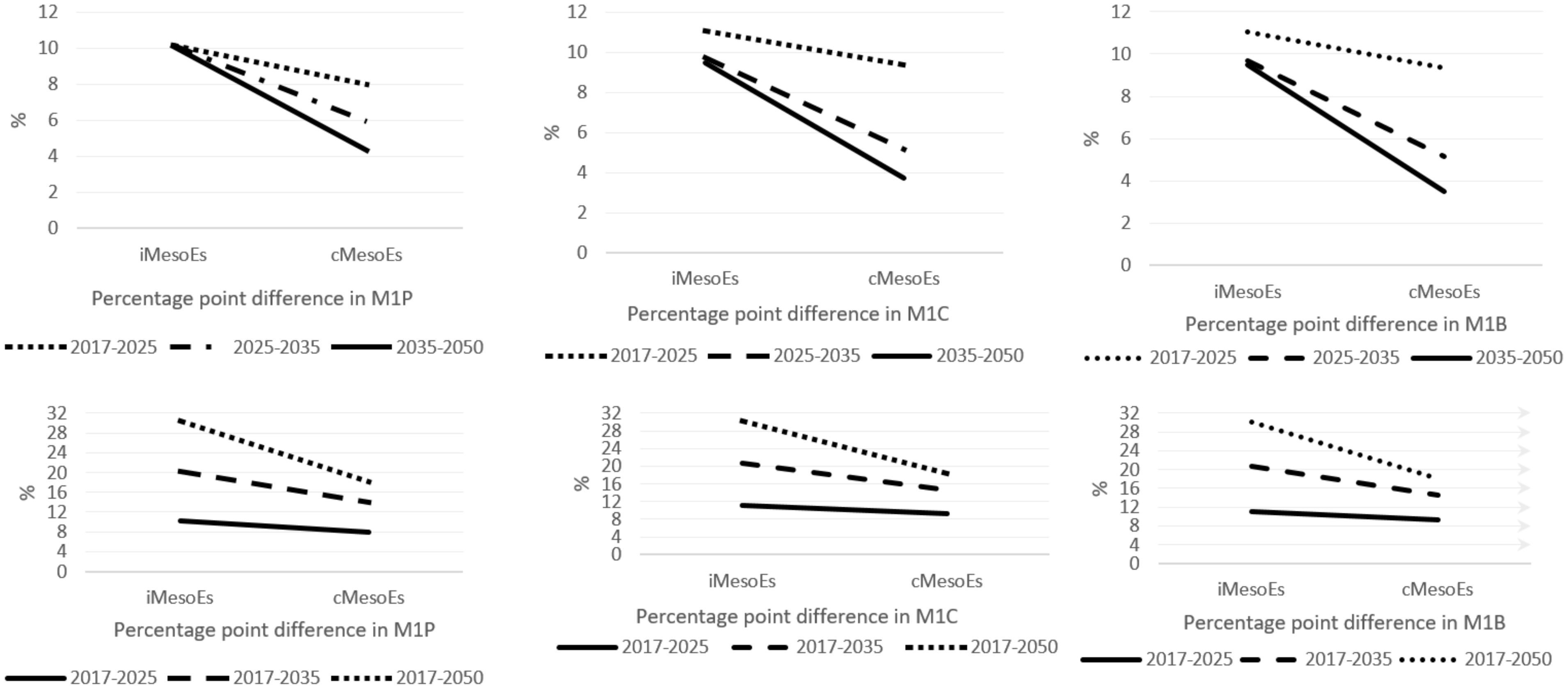


Figure 34 Percentage point differences between the M1 scenarios

6.6.1.2 Sefficiency for M2P

Both inflow and consumptive efficiency (iE_s and cE_s) values for M2P1, M2P2 and M2P3 scenarios go down significantly compared to inflow and consumptive efficiency for M2P0. This suggests that useful outflow per unit of useful inflow decreases, and useful consumption per unit of effective consumption decreases relative to the reference.

The cE_s for M2P0 show better performance results at both levels of Sefficiency (Figure 35). The highest difference is between M2P0 and M2P3, making the relative consumptive impact of M2P3 on the basin (and both WUS and the basin in case of Meso) rather high (refer to Figure 36). The impacts are highest when the applied water to KCWS (RP_{KCWS}), return flow from KRIP and wastewater from Kano Metropolis increased by more than 500%, 15% and 200% respectively, and volume of water downstream decreased by 50%. This indicates that due to the high increase in population, much more water is required for urban water supply (and hence generating more wastewater due to anthropogenic and agricultural activities) thereby decreasing the quantity and quality of water downstream. Hence, population growth will result in decreasing the performance of Kano River.

The lowest difference happened between inflow efficiency values, i.e., iE_s for M2P2 and M2P3 (Figure 36). The useful outflow compared with useful inflow for the basin (or WUS and basin) are slightly higher than M2P3, while the other two show significantly higher values (i.e., between M2P0 and M2P1, and M2P1 and M2P2). This happened with a reduction of 35% in VD and increase of 84%, 60% and 10% in applied water to KCWS (RP_{KCWS}), wastewater from Kano Metropolis and return flow from KRIP, respectively. See Figure 36 and Appendix for a difference between percentage points for M2P.

For the M2P case, high levels of water abstraction and useful consumption values are dominant factors. A minimum value of flow in the river (VD) is required by law, while water supply through RP and NR are highly desired for KCWS and KRIP, respectively. However, in 2025 the Usefulness Criterion ‘‘s’’ for RP_{KCWS} (0.7) and

NR_{RKR} (0.7) are higher than VD (0.6), meaning that minimum flow requirement of the river is less useful than the water allocated to KCWS and KRIP. This is the case in all the other scenarios.

The quantitative efficiencies (E_b) do not change even though quantities change up to 500% because beneficial weights (W_b) stay the same. This agrees with other efficiency terms that do not have quality in their equations show the same efficiency although quality changes (see Figure 35). In other words, although the quantities change, their average fractions remain the same. This shows that beneficial weights are dominant variable in this case. Considering these scenarios, water quality has an influence on the performance of Kano River under the influence of population growth.

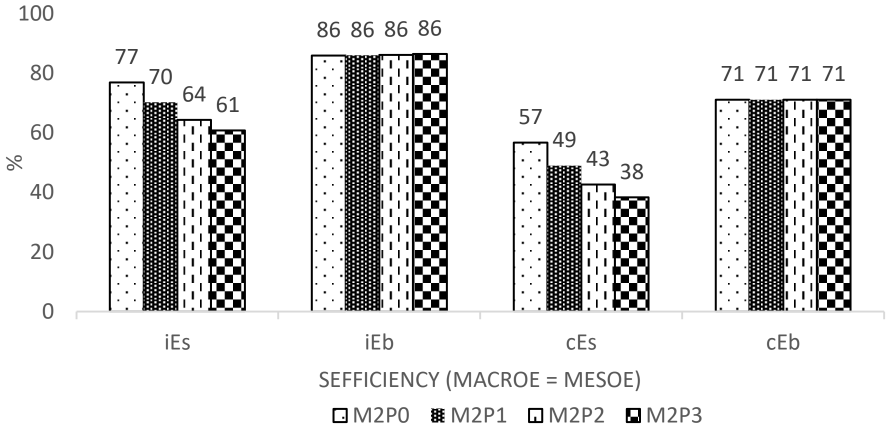
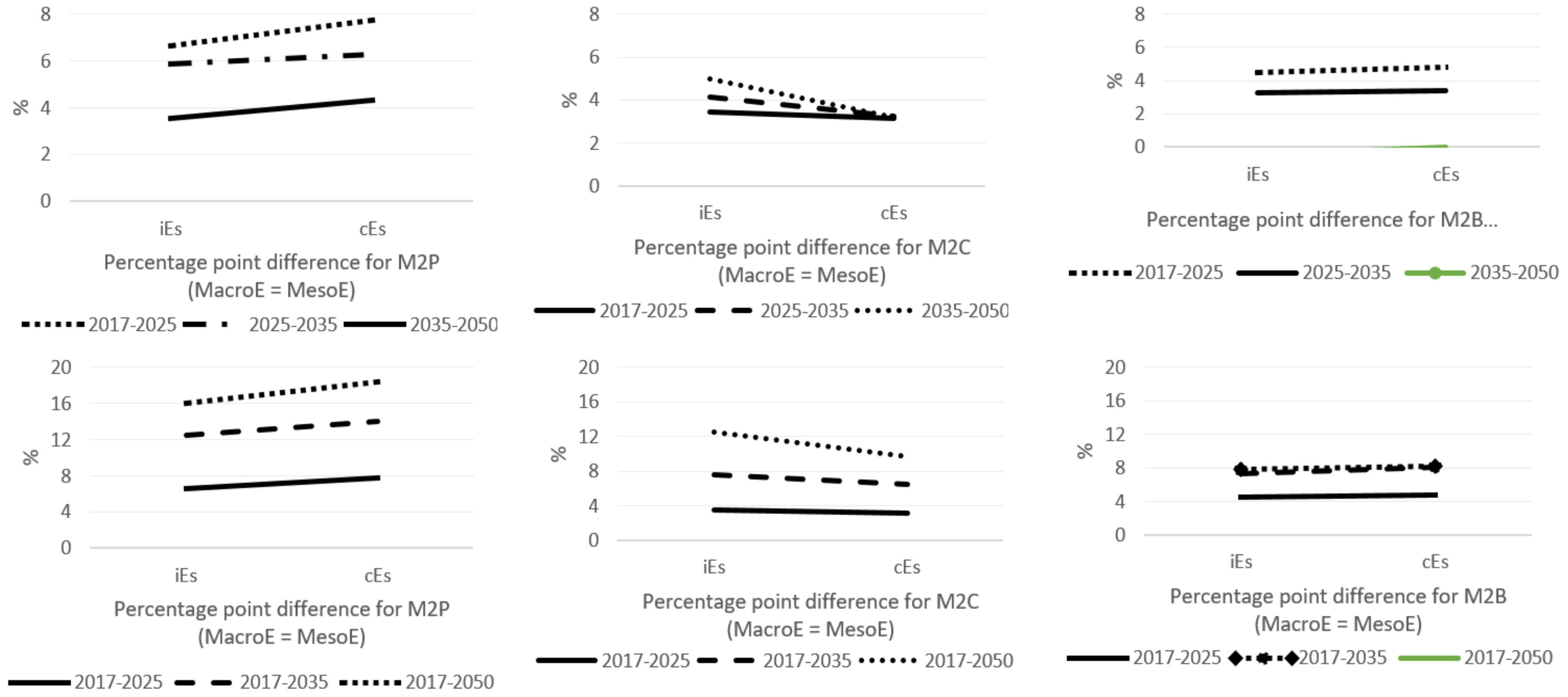


Figure 35 Sefficiency for M2P


Percentage point difference for M2P (MacroE = MesoE)

Percentage point difference for M2C (MacroE = MesoE)

Percentage point difference for M2B...

Percentage point difference for M2P (MacroE = MesoE)

Percentage point difference for M2C (MacroE = MesoE)

Percentage point difference for M2B (MacroE = MesoE)

Figure 36 Percentage point differences between the M2 scenarios.

6.6.2 Sefficiency results based on climate change

Results of Sefficiency for the two models based on climate change scenarios are presented in the next subsection.

6.6.2.1 Sefficiency for M1C

Both inflow and consumptive meso-efficiency (iMesoE$_s$ and cMesoE$_s$) values for M1C1, M1C2 and M1C3 scenarios go down significantly compared to M1C0. This suggests that useful outflow per unit of useful inflow decreases, and useful consumption per unit of effective consumption decreases relative to the reference.

The cMesoE$_s$ for M1C0 shows better performance results (Figure 37). The highest difference is between M1C0 and M1C3, making the relative consumptive impact of M1C3 on the WUS and basin rather high (Figure 36). The impacts are highest when ET increases by 5.3%, indicating higher evapotranspiration due to temperature rise. Hence, the rise in temperature decreases the performance of KRIP. However, considering an increase in ET - a crucial water-flow path for agricultural systems - and having in mind that it is linearly proportional to yield (Steduto, Hsiao, & Fereres, 2007), one would expect an increase in the performance instead of decreasing. Albeit evapotranspiration increases, so is the applied water containing chemicals (fertilizers and pesticides) thereby generating more pollution and hence the decrease in performance. This underscores the fact that focusing on one flow can totally miss a proper water management and design policy. For iMesoE$_s$, the difference between inflow efficiency values for all the scenarios show significant changes (Figure 34). The useful outflow compared with useful inflow for the WUS and basin of M1C is significantly lower.

Unlike full inflow and consumptive meso-efficiency, quantitative meso-efficiency (E$_b$) values for climate change show increasing trends, i.e., the performances change across the scenarios with a maximum of 3 pp in 2050. According to our assumptions, the relative quantity changes are very small, consequently performance increases happened because water quality is not considered (in other words assuming the quality weight of water to be 1) and relative quantities remain the same while beneficial consumption $(ET + NR)_b$ - mainly ET - increases. In the same manner, CE also started to show increasing trend. In these scenarios, global warming has more influence on KRIP than population growth considering the impacts it has on both full and beneficial meso-efficiency (see Figure 34 and Appendix for a difference between percentage points for M1C).

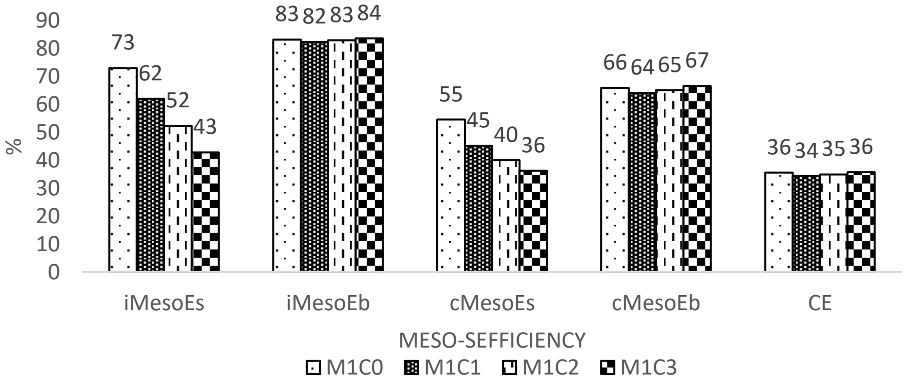


Figure 37 Sefficiency for M1C

6.6.2.2 Sefficiency for M2C

The inflow and consumptive efficiency (iE_s and cE_s) values for M2C0 are slightly higher than M2C1, while M2C2 and M2C3 scenarios go down significantly. This suggests that useful outflow per unit of useful inflow decreases, and useful consumption per unit of effective consumption decreases relative to the reference.

The cE_s values for all M2C scenarios show slightly higher values compared to one another, with M2C2 and M2C3 having a difference of 4 pp while the other two exhibit lower values (3 pp) (see Figure 36). The impacts are highest when VU or VA is decreased by 10% and VD by 18%, while ET and evaporation increased by 5.3 and 9.2% respectively. Other WaP quantities are increased or decreased as presented earlier in Table 34. This indicates that due to climate change (global warming is more pronounce and little increase in precipitation) volume of water in Kano River - both upstream and downstream - is reduced thereby limiting the water usage. Not only does the water physically removed from the WUS as a result of evaporation and ET, but also the resulting pollution has put it in such a degraded state with little benefits. It is worth mentioning that quantity of precipitation in a year is different from its distribution annually. Most of the times, climate change is intensifying meaning that the increase in annual precipitation happens with fewer precipitation events. This is also true in Kano (Mohammed et al., 2015). Hence, considering these scenarios and having in mind that the effect of precipitation is negligible, we can say that global warming results in decreasing the performance of Kano River.

The lowest difference happens between inflow efficiency (iE_s) of M2C0 and M2C1 (Figure 36). The useful outflow compared with useful inflow for the basin (or WUS and basin) are slightly higher than M2C1. While M2C3 shows significantly lower values. This happened with an increase in precipitation by 1.4% (which is relatively little) and return flows from KRIP by 5%. For M2C case, water reduction through non-useful consumption are dominant factors, in other words, a substantial amount of water is lost due to increased evaporation and non-beneficial evapotranspiration. Figure 36 and Appendix display differences between percentage points for M2C.

The quantitative efficiency (iE_b and cE_b) values for climate change is rather curious. It shows decreasing trends unlike that of population growth that stay the same. An explanation to this is that quantities with higher beneficial weights (W_b) are decreasing in all the different scenarios while those with very low beneficial weights are increasing. Alternatively, iE_b and cE_b values are decreasing due to the assertion that evaporation and ET have less beneficial values in Kano River (please refer to W_b values in Table 37). This is an interesting result of how Sefficiency can reveal the trade-offs between quantity, water pollution, and water value at multi-level governance with climate descriptors and stakeholder enablers.

With all our assumptions, it shows that water quantities changes have an influence on the performance of Kano River model under climate change. However, Kano River model is less sensitive to climate change impacts mainly due to the influence of global warming which is more pronounced than precipitation which can be considered to have little influence. Although global warming creates more consumption through evaporation, ET and evaporation have lower values relative to other flows. The impact which is basically percentage increase in ET and evaporation becomes a small amount, however, the driver is substantial.

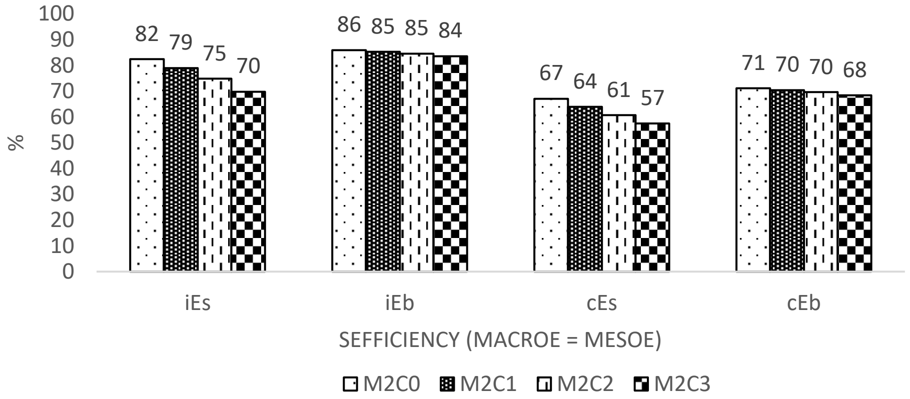


Figure 38 Sefficiency of M2C

6.6.3 Sefficiency results based on population and climate change impact

Results of Sefficiency for the two models based on cumulative impacts of population and climate change scenarios are presented in the next subsection.

6.6.3.1 Sefficiency for M1B

This sub-section now examines the impacts of both population growth and climate change on performance of KRIP concurrently. The inflow and consumptive meso-efficiency (iMesoEs and cMesoEs) values for M1B1, M1B2 and M1B3 scenarios go down significantly compared to M1B0. This suggests that useful outflow per unit of useful inflow decreases, and useful consumption per unit of effective consumption decreases relative to the reference.

The cMesoE$_s$ for M1B0 shows better performance results of Sefficiency (Figure 39). The highest difference is between M1B0 and M1B3, making the relative consumptive impact of M1P3 on the WUS rather high (see Figure 34 above). The impacts are highest when applied water to KRIP and ET increase both by 25%. This indicates that high increase in population and temperature rise resulted in decreasing the performance of KRIP. As a result of population growth much more land and water is required for planting and consequently generating more pollution. At the same time, evapotranspiration increases due to temperature rise which further compounded the problem.

For iMesoE$_s$, the difference between inflow efficiency values for all the scenarios show significant changes. The useful outflow compared with useful inflow for the WUS and basin of M1B is significantly lower. Refer to Figure 34 and Appendix for a difference between percentage points for M1B. Another result that may have to do with the trade-offs is quantitative meso-efficiency values for M1B showing rather mixed results, in other words, increasing and then decreasing, i.e., the performance changes across the scenarios. This happened because the WaP quantities increase even though all the quality weights decrease. However, CE remain as it is in M1C.

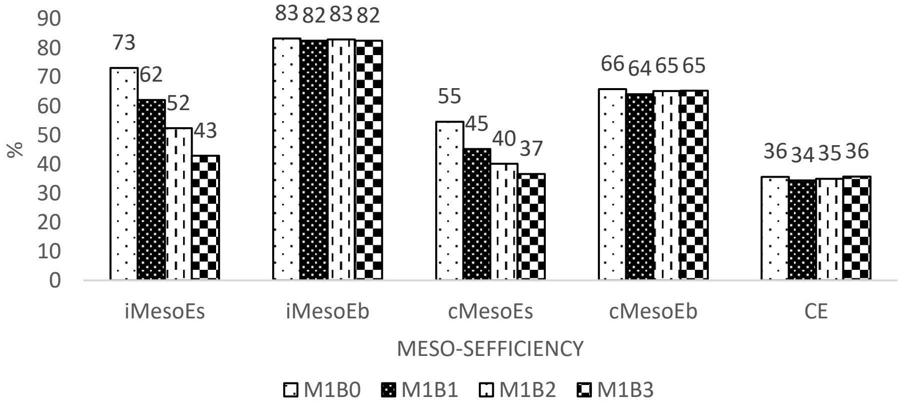


Figure 39 Sefficiency for M1B

6.6.3.2 Sefficiency for M2B

This sub-section examines the concurrent impact of population growth and climate change on the performance of Kano River basin. The inflow and consumptive efficiency (iE_s and cE_s) values for M2B0 are significantly higher than M2B1, while M2B2 and M2B3 values are practically equal (Figure 38). In the case of M2B1, the useful outflow per unit of useful inflow decreases, and useful consumption per unit of effective consumption decreases, while for M2B2 and M2B3 the useful outflow per unit of useful inflow and useful consumption per unit of effective consumption can be considered the same.

The cE_s for M2B0 show better performance results at both levels of Sefficiency (Figure 41). The highest difference is between M2B0 and M2B1, making the relative consumptive impact of M2B1 on the basin (and both WUS and the basin in case of Meso) rather high (see Figure 36 and Appendix). But M2B2 and M2B3 have the same inflow and consumptive efficiency (iE_s and cE_s) values of 72% and 54%, respectively, despite changes in the WaP quantities and qualities (all the quality weights decrease and some WaP quantities increase while others decrease). Although they have the same efficiency, M2B3 happened with a reduction of 70% in VD (125 Mm^3) as shown in Table 42, bringing the available water downstream below the minimum volume set (135 Mm^3). This indicates that under this scenario Kano River basin will be under water scarcity. It is found that water demand increases more within urban sector than it will in agriculture (Figure 40), because KRIP is already getting enough water. In general, potential demands for water in the basin will far exceed the available supply by 2050.

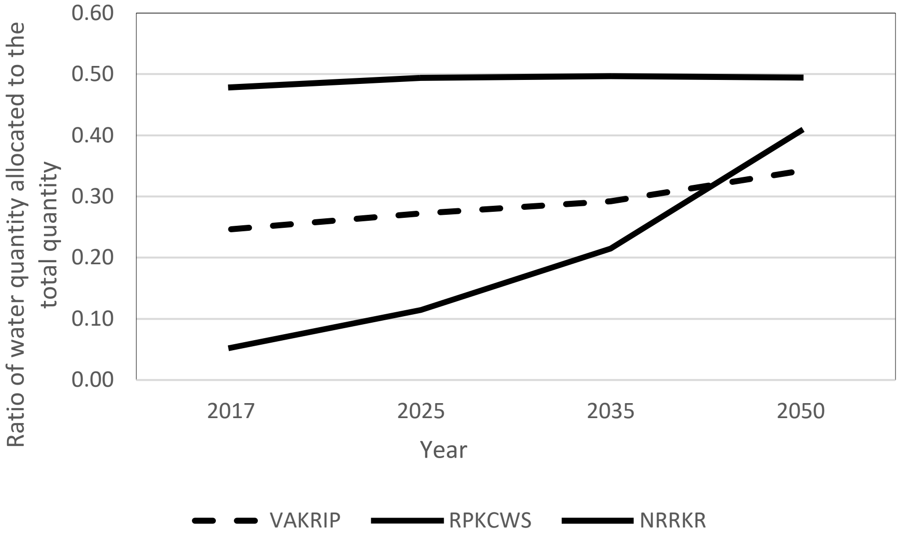


Figure 40 Ratio of water allocated to users to the total quantity

The quantitative efficiency (iE_b and cE_b) values for M2B behaves in a similar manner as M2C, showing decreasing trends. The quantities with higher beneficial weights (W_b) are decreasing while those with very low beneficial weights increases. Alternatively, iE_b and cE_b values are decreasing due to the assertion that evaporation and ET have less beneficial value (please refer to W_b values in Table 37).

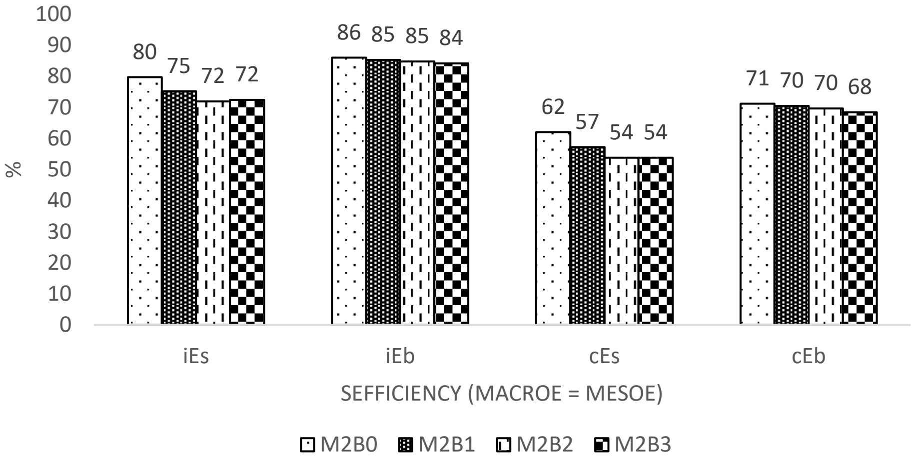


Figure 41 Sefficiency of M2B

6.7 Conclusions

Few studies in the study area considered both drivers of change to analyse and compare their sensitivity to expected changes in temperature and precipitation due to climate change and population growth. In this study, we evaluated impacts of climatic change and population growth on the performance of Kano River basin and KRIP, using an integrated approach that includes quality, quantity, and benefits called Sefficiency.

We found that performance of KRIP and Kano River for the current population and global warming was degraded significantly under projected population and future climate conditions. The results of this research suggest that the performance of KRIP and Kano River basin are sensitive to population growth and climate change under the scenarios considered. However, Kano River is less sensitive to global warming impacts population growth is the dominant driver of change. Moreover, combined effect of population and climate change impact in Kano River basin will result in a reduction of downstream water by 70% to below the recommended volume of 135 Mm^3 by 2050 (i.e., to 125 Mm^3). By then the potential demands for water in the basin will far exceed the available supply.

Even though W_b stays the same in all M2P scenarios and quantities change, but quantitative efficiencies (E_b) do not change. This is in line with other efficiency terms that do not consider quality in their equations and show the same efficiency although quality changes. Considering these scenarios, it indicates that water quality has the dominant influence on the performance of Kano River under population growth. On the other hand, the quantitative efficiency values for M2C shows decreasing trends unlike that of population growth mostly due to the assertion that evaporation and ET have less beneficial value. Alternatively, quantities with higher beneficial weights (W_b) are decreasing while those with low beneficial weights are increasing. For KRIP, unlike full inflow and consumptive meso-efficiency, quantitative meso-efficiency values for climate change show increasing trends because water quality is not considered and relative quantities remain the same while beneficial consumption increases.

Considering an increase in ET, one would expect an increase in the performance of KRIP, however, due to increase in farmlands more pollution is generated thereby decreasing its performance. This underscores the fact that focusing on one flow can totally miss a proper water management and design policy.

Finally, it can be concluded without any doubt that population growth and global warming will decrease the performance of both KRIP and Kano River basin. Increases in water demand within agricultural KRIP will primarily be due to higher irrigation demand caused by population growth. In Kano River model, increases will be due to rise in evaporation under higher temperatures. On the other hand, urban water demand will increase due to population growth. Overall, water demand will increase significantly within urban sector than it will in agriculture in Kano River basin. In general, potential demands for water in the basin will far exceed the available supply by 2050.

It is recommended that efficient management and use of water regarding the qualitative as well as quantitative aspects of water resource use is very critical in Kano River basin. However, dealing with pollution by using wastewater treatment plants will improve the efficiency of both the WUS. This study can be regarded as the first step and future studies may use the described methodology using more encompassing technologies such as remote sensing and GIS to derive better data such as the actual irrigated land, flow rates, groundwater recharge, irrigation schedules, etc. Our results point to the need for future in-depth studies to understand the dynamics of the trade-offs that influences the quantitative efficiencies (iE_b and cE_b) since we are talking about understanding 30 D space (one equation and about 30 variables) which is highly complex. This is in light of the fact that Sefficiency values started to have an irregular pattern (decreasing and increasing as time increases) as all the quality weights decrease and some WaP quantities increase while others decrease.

CHAPTER SEVEN
CONCLUSIONS AND RECOMMENDATIONS

7.1 Management and farmers' perspective on water management in KRIP

Sefficiency, a new framework was used to evaluate the performance of Kano River Irrigation Project at meso level looking at it from two different perspectives of major actors in Kano basin. Two major stakeholders, namely, water managers and farmers, were contacted in order to evaluate their reasoning in relation to the value of water in the basin. Regional water managers have a much broader view of water needs and impacts, such as, pollution and groundwater depletion, than farmers, and consequently, can better relate useful flows and (effective) consumptions for sustainable management, including technological investments. Efficiencies using this approach are higher than the classical ones, which lacks comprehensive treatment of an irrigation system. Hence, we suggest the use of the full meso efficiency (MesoE$_s$) of the management perspective for proper policy analysis for Kano basin. This is due to the fact that management is more holistic and, contrary to the farmers, includes both groundwater and downstream users in defining management practices. Kano River Irrigation Project, a major water user on Kano River which eventually flows into the Lake Chad, one of the most important transboundary water bodies in Africa, should be properly managed by employing the Sefficiency framework, which puts water as the central issue for policy making, particularly in water scarce countries.

7.2 Impacts of population growth and global warming on performance, water allocations, water availability and sustainability

A comprehensive performance assessment of two major water users in Kano River basin reveals that the performance of KRIP and Kano River model for the current population and global warming decrease significantly under projected population and future climate conditions. However, Kano River model is less sensitive to global warming impacts population growth is the dominant driver of change. Moreover, the cumulative effects of population and climate change impact in Kano River basin will result in a reduction of downstream water below the recommended volume. Under global warming, increases in water demand within agricultural KRIP will mostly be due to higher irrigation demand (ET). While in Kano River, increases will be due to rise in evaporation under higher temperatures. On the other hand, urban water demand will increase due to population growth. Overall, water demand will increase more significantly within urban sector than it will in agriculture. In general, potential demands for water in the basin will far exceed the available supply by 2050. The changing climate and population growth in the basin further added to the complexity of water management issues and require immediate attention for sustainable water (re)allocation.

The quantitative efficiencies (E_b) do not change even though the quantities change while W_b stays the same in all M2P scenarios. This in conformity with other efficiency terms that do not consider quality in their equation and show the same efficiency although quality and quantity change. On the other hand, the quantitative efficiency values for M2C shows decreasing trends unlike that of population growth mostly due to the assertion that evaporation and ET have less beneficial value relative to other flows. For KRIP, unlike full inflow and consumptive meso-efficiency, quantitative meso-efficiency values for climate change show increasing trends because water quality is not considered and relative quantities remain the same while beneficial consumption increases. Increasing ET, one would expect an increase the performance of KRIP, but considering other flows the performance decreases. This underscores the fact that focusing on one flow can totally miss a proper water management and design policy.

Kano River plays a significant role in contributing to water allocation to KRIP and KCWS, and also to groundwater recharge which is highly desired for downstream wells and to environmental flows. However, the results suggested that the WUS itself is not efficient in using its water resources, because MicroEs value is very low. Increasing the effective consumption in terms of decreasing the pollution caused by anthropogenic activities is the pathway to achieving better results. Moreover, as it was mentioned MicroE is similar to CE and as such caution should be taken in its use.

7.3 Addressing methodological issues in the performance assessment and indicators

Agricultural performance assessment dominated the literature with urban water assessment being the less reported. More so, performance assessment of municipal water systems is strongly oriented by a management/economic perspective, and technical aspects have often been ignored. Indicators that include adequacy, efficiency, dependability, and equity have been widely used to assess the irrigation and urban performance. Furthermore, the study revealed a lack of standardization and use of a wide range of indicators to assess the performance. As yet, however, there is no globally agreed format for performance assessments and indicators. This makes comparisons between studies on efficiency and other indexes complicated since different indicators were adopted across studies. Majority of researchers proposed new indicators considering water reuse and distinguishing between beneficial and non-beneficial, and consumptive and non-consumptive water uses.

Followings are the shortcomings or issues related to the available methods based on the literature review conducted:

i. Lack of initiating definition of efficiency.
ii. Consensus has not yet emerged in models to be applied.
iii. Lack of availability of standard procedure or main referenced procedure.

Consequently, it was recommended that a set of terms be widely used for easy and shared understanding among all stakeholders. In our opinion, Sefficiency is better candidate, because it advances systemic and comprehensive performance indicators based on a universal principle that integrate differentials and trade-offs of water quantity, quality and beneficial uses at multi-level management and planning with climate descriptors and stakeholder enablers.

7.4 Contribution and innovative aspects of this research

This PhD research contributes directly to understanding the present situation in Kano River basin. It presents the first and most recent performance assessment of the water users in the basin. To the best of knowledge of the researcher, there are no published studies that assessed the performance of any water user in the study area. In general, this research contributes to improving understanding of basin-scale performance assessment exhibited in macro, meso and micro scales in a semi-arid basin which is data scarce. The knowledge and models generated by this study is helpful to serve as an input in the sustainable management of water resources in a river basin context for the Kano River Basin, and similar regions of Nigeria and elsewhere. It could also serve as a foundation for further research in the basin and Nigeria in general.

Few studies in the study area considered both drivers of change to analyse and compare their sensitivity to expected changes in temperature and precipitation due to climate change and population growth. In this study, we evaluated the cumulative impacts of climatic change and population on the performance of Kano River and KRIP, using an integrated approach that includes quality, quantity, and benefits called Sefficiency.

The main innovative aspects and contributions of this research include, but are not limited to the following. First, the methodology used, i.e., Sefficiency (Sustainable efficiency) is quite new, innovative and highly relevant to water resources management and planning including many areas of hydrotechnical and environmental engineering. For evaluation and performance assessment, Sefficiency can provide a good overview, and point to where in-depth studies are needed. For planning, Sefficiency gives some key information that is useful in deriving policies for water savings. Interesting results emerged due to stakeholder involvement in deriving usefulness criterion of the flow paths that will have a great influence on water policy in Kano river basin. Second, the case study is crucial because very few water reports and papers are written about this critical part of the world as confirmed by a recent World Bank report. Nigeria is the most populous African nation and it is getting the attention of the world due to its rapid increase in population and the intensification of the highly problematic water-food-climate change triangle. Third, improved knowledge on performance assessment and indicators of water resources systems, through use of rigorous state-of-the-art methods, including development and application of new innovative techniques. Several aspects of performance evaluation have been identified, varying from country to country, from utility to utility and depending on the specific objectives and the different stakeholders involved in each case.

In general, the study provided a scientifically important and practically relevant example of performance assessment and its use in the water resources planning and management in the river basin context, which is instructive for the Kano River basin, and other river basins of Nigeria, and worldwide.

7.5 Major recommendations and future directions

The following water management and policy actions are recommended based on the study findings. It is evident that pollution and evaporation increase the non-beneficial consumption in Kano River basin. Therefore, farmers should be educated on the importance of their return flows for basin water allocation and the necessary care for lowering their pollution impact. Moreover, dealing with pollution by using wastewater treatment plants will improve the efficiency of both the WUS and consequently the basin in general. In a nutshell, it is recommended that efficient management and use of water with regard to qualitative as well as quantitative aspects of water resource use is very critical in Kano River basin.

The present supply driven allocation is not sustainable and its thorough revision is recommended. The sectoral water allocation needs to be revised considering resource availability and demand, a sound foundation of which has been laid in this study. Because of the high share of water allocation for urban and agriculture, potential demands for water in the basin will far exceed the available supply in the near future, having a considerable impact on downstream water availability. More so, the hydropower project embarked by Kano State government raises concern. Therefore, further assessment of the environmental water needs is highly recommended.

This study can be regarded as the first step and future studies are recommended to improve the performance assessment of water systems and to overcome the limitations of the present work. First of all, it would be helpful to improve the set of data using remote sensing and GIS, such as the actual irrigated land, flow rates, groundwater recharge, irrigation schedules, etc. A detailed study on evaporation loss and measures to reduce it from Kano River basin is recommended. Furthermore, another interesting study would be a national comparison with other river basins to identify the specificity of each and the relative strengths and weaknesses. However, information availability appears to be a prerequisite for performance measurement. It appears that access to reliable information and the capacity to manage it reliably constitutes a handicap for Kano River basin. In view of that, more studies and investments should be made on data collection and better use of available (scarce) data sets. Use of smart systems is recommended, particularly for improving water balance flow paths and their qualities.

Our results point to the need for in-depth studies to understand the dynamics of the trade-offs that influences Sefficiency since we are talking about understanding 30 D space (one equation and about 30 variables) which is highly complex. This is in light of the fact that quantitative efficiencies (iE_b and cE_b) values started to either decrease or increase as some of WaP quantities increase while others decrease.

The Sefficiency model application demonstrated in this study should be extended by testing other “what if” scenarios (e.g., water user associations, before and after the TRIMING intervention project funded by World Bank, and wastewater treatment plants).

SCIENTIFIC OUTPUT

1. Ahmad MT, Haie N, Yen H, Tuqan NAN (2017) Sefficiency of a water resources system: The case of Kano River Irrigation Project, Nigeria. *Int J Civ Eng.* Doi: 10.1007/s40999-017-0235-2. https://link.springer.com/article/10.1007/s40999-017-0235-2

2. Ahmad MT, Haie N, Yen H (2018) Analysing the impact of population growth and climate change on performance of water use systems in Kano river basin, Nigeria. (*under preparation)*

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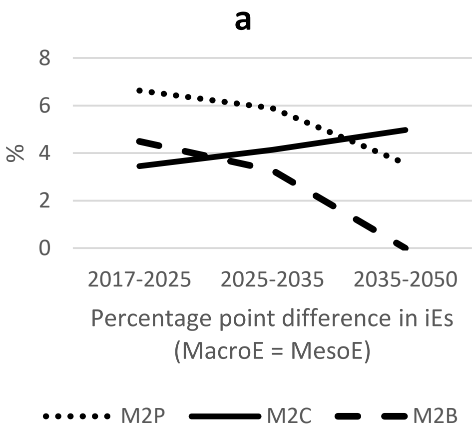
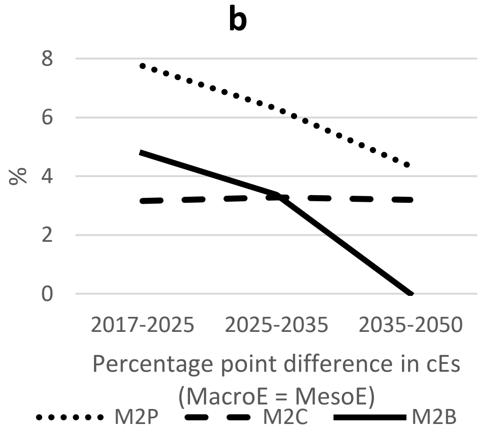
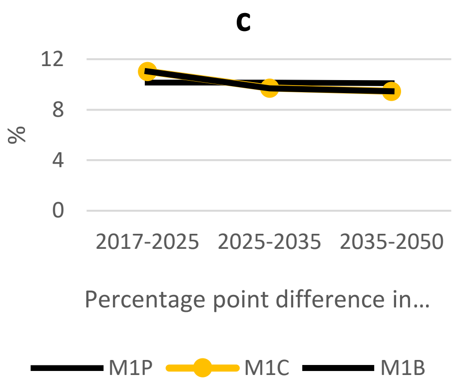
APPENDIX

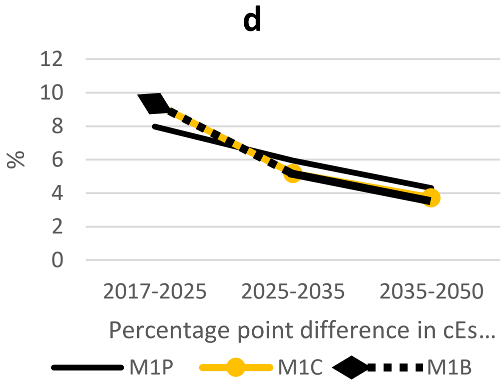
Appendix 1 Graphs showing percentage point differences between scenarios

Figures on percentage points presented in chapter six and the ones below come from the same data, but convey difference results as viewed from different perspectives for easy comparison within and across scenarios.









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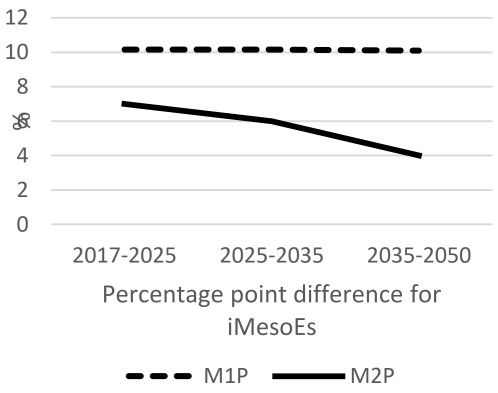
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2035-2050
Percentage point difference for iMesoEs
M1P
M2P

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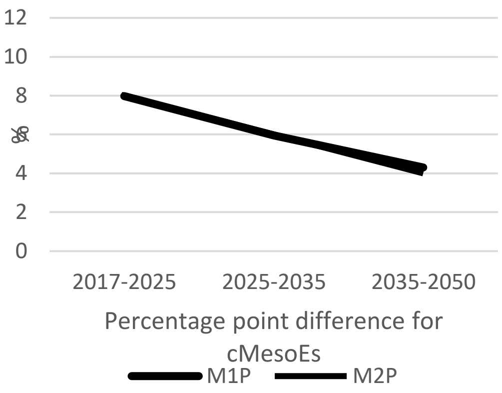
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Percentage point difference for cMesoEs
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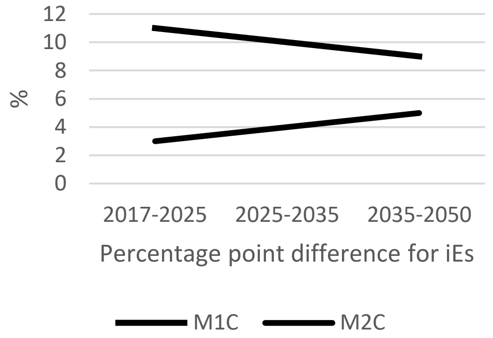
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Percentage point difference for iEs
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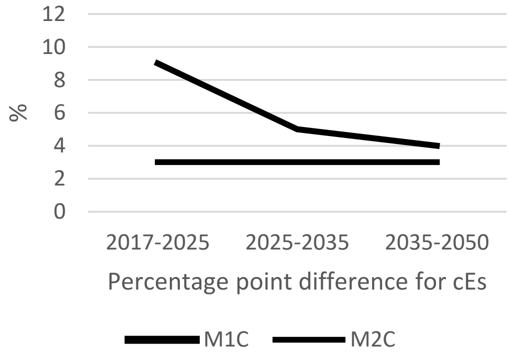
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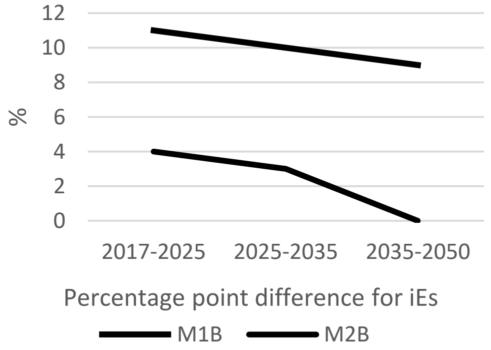
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Percentage point difference for iEs
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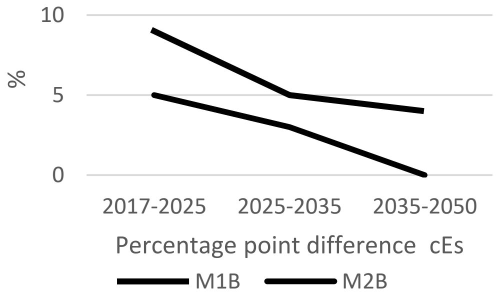
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2025-2035
2035-2050
Percentage point difference cEs
M1B
M2B