Water allocation assessment in semi-arid region under data scarce conditions: a study of Kano basin

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Abstract- Growing population and demand for food and competition between different water users increase pressure on water resources especially in semi-arid of developing countries like Northern Nigeria. In addition, water resources management is complicated due to global warming and other regional economic and environmental problems. Improving how water is allocated to urban and agricultural schemes is considered a vital issue for addressing the pressure on water resources. This paper explores the use of Monte Carlo simulation in water management and its possible application in water allocation problem in Kano basin, which in turn can provide a sound basis for water (re)allocating policies. Streamflow allocations in each period to KCWS and KRIP was established. This is an on-going research, further work will constitute generating probability values using central limit theorem which is going to be used in the model using spreadsheet or MATLAB consider each of the allocations as random variables for KRIP and KCWS respectively.
Keywords –Water allocation, Monte Carlo, Kano River basin, water resources management, semi-arid regions

I. INTRODUCTION

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 (FAO 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 (Faramarzi et al., 2013; Hall et al., 2017; IPCC, 2014; Kifle Arsiso et al., 2017; Niang et al., 2014). Improving water allocation to urban and agricultural schemes through is considered a vital issue for addressing the pressure on water resources.

Allocation of water resources in river basins is one of the critical issues. Water allocation should consider three key principles: equity, efficiency and sustainability (Haie and Keller, 2014; UNESCAP, 2000 cited in Wang et al. 2008). Thus, an integrated analysis at the watershed-scale would be valuable, where individual water related sectors (stakeholders), such as agricultural, municipal, and industrial water supply are brought together in a framework (Bangash et al., 2012; Wang et al., 2008). Water allocation is based on some factors ranging from historical, institutional, legal, political and social conditions (Bangash et al., 2012). Disagreements arise many times due to different competing water users for a limited resource, for sustainability this can be solve through reforming institutions and methodologies responsible for water allocation particularly in places with water shortages. Stakeholders play significant role in reallocating water properly based water rights, through water market or regulated water transfers (Wang et al., 2008). For effective water resources management of a river basin, methods of modelling and analysis for assessing the capability of the system are crucial (Wurbs, 2005). Bangash et al., 2012 state that '[……..]Integrated strategic scale resource management models should be capable of reproducing the physical behaviour of the system, with a realistic representation of the different surface and groundwater resources, including their interaction, and the spatial and temporal variability of resource availability'.

Many mathematical models have been developed in order to assess water resources management especially water allocation. Most of the water allocation simulation models are based on mass balance principles and use a network linear program with user-defined priorities to allocate resources in a river system like MODSIM-DSS (Fredericks et al., 1998), MIKEBASIN (DHI, 2006), WEAP (Yates et al., 2005; McCartney and Arranz, 2007), WRAP (Wurbs, 2015), HEBRM-MOPEC (Britz et al., 2013) and REALM (Perera et al., 2005).

Wurbs (2005) develop and use a generalised modelling system called Water Rights Analysis Package (WRAP) that asses the availability and reliability of water resources in the State of Texas. Reservoir/river system management and water allocation are simulated using past hydrological data. One of the advantage of WRAP is that it simulates management of the water resources of a river basin or multiple-basin region under a ‘’priority-based’’ water allocation system as well as evaluating water availability for new and existing requirements. The model can be use in any river/reservoir/use system, with input files being developed for the particular river basin of concern. However, the model will best be use when there are sufficient data.

In order to achieve sustainable water resources management in a data scarce low-flow river watershed, Bangash et al. (2012) investigate the use of hydrological modelling software for efficient use and allocation of water to different sectors in order to propose tools that could be used to support decision-making complying with European Union Water Framework Directive (EUWFD). Bangash et al. (2012) describe MIKE BASIN as a mathematical representation of the river basin, including the configuration of the main rivers and their tributaries, the hydrology of the basin in space and time, and existing as well as potential major water use schemes and their various demands for water. It portrays a better model to be use in this study. MIKE BASIN is an integrated water resource management and planning computer model that integrates GIS with water resource modelling (DHI, 2006). However, there are certain limitations such as the inability to simulate erosion and sediment transport and the model comes as a commercial package. Doulgeris et al. (2015) analysed the effect of water deficit on crop yield and net profit for some periods in the irrigation module of the MIKE BASIN model. Chang et al. (2016) proposed intelligent water resources allocation strategies for multiple users through hybrid artificial intelligence techniques implemented for reservoir operation optimization and water shortage rate estimation. In another effort, Wang et al. (2008) developed Cooperative Water Allocation Model (CWAM) and applied it on the South Saskatchewan River Basin. It comprises of initial water rights allocation and subsequent reallocation based on economic net benefits.

Britz et al. (2013) propose a new solution format for Hydro-economic river basin models (HERBM) based on Multiple Optimization Problems with Equilibrium Constants (MOPEC) that allows solving simultaneously problems involving numerous water users that maximize each an independent objective function (further called ‘independent optimization’ IO) while their resource use is still interrelated. The location of a firm in the water distribution network can be seen as one example of asymmetric access to resources (Britz et al., 2007). In addition, Hassanzadeh et al. (2014) developed an integrated water resources management model for Saskatchewan called SWAMP1.0 that includes irrigation demand, and economic evaluation sub-models, and has the capability to investigate alternative environmental flow conditions that can be used in practice by decision makers.

In the Nigerian context, Barbier (2003) modelled the economic and hydrological impacts of upstream water diversion on downstream floodplain activities of the Hadejia-Jama’are River Basin, northern Nigeria. Ezenwaji et al. (2014) employed the linear programming modelling technique to optimise the allocation of water produced daily by the State Water Corporation and supplied to the four sectors of the town. This paper explores the use of Monte Carlo simulation in water management and its possible application in water allocation problem in Kano River basin, which in turn can provide a sound basis for water (re)allocating policies.

II. METHODOLOGY

2.1 Description of the study area and key issues

The Kano river basin is located in northern part of Nigeria (Figure 1). It is a sub-catchment of the Hadejia River which eventually terminates in Lake Chad, an important transboundary basin in West Africa shared with Chad, Cameroon, Niger, and Nigeria. Kano River is being drained by Rivers Kano and Challawa, and their tributaries – Watari, ‘Yarkuto, Tatsawarki, and Salanta (Bichi and Anyata, 1999). A brief description of the study area and key issues is presented below.

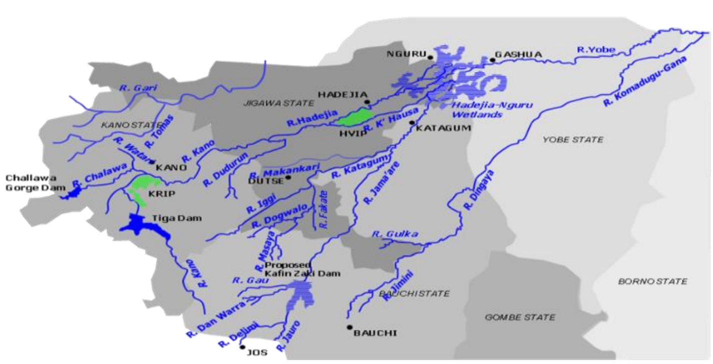

Figure 1 Kano River basin showing the main water users (KRIP and KCWS)

The climate is semi-arid. The precipitation exhibits large spatial and temporal variability. The mean annual precipitation is about 898 mm, and maximum and minimum values are 1872 mm and 419.6 mm respectively. Temporal trends show that most of the total precipitation falls within the five months (May-September) with August having the highest amount, whereas November-March form the dry periods (Mohammed et al., 2015). Evaporation demand is generally higher than precipitation. The mean annual temperature ranges from 26°C to 32°C, with the high diurnal temperature ranges of 13.1°C and relative humidity of 17%-90%. Temperatures are highest in the late dry season in April and May with mean daily minimum temperatures of 24°C and an average daily maximum of 38°C. The coldest month is January with mean daily minimum temperatures of 13°C and an average daily maximum of 30°C. Evaporation is in the range of 3,500 mm to 4,500 mm per year.

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 Kano River is regulated by Tiga dam (the largest dam in the basin), having a designed storage capacity of about 1,429 Mm^3 (and live storage capacity of about 1,283 Mm^3), is a multi-purpose dam aimed for providing irrigation water to about 22,000 hectares (ha) in the Kano River Irrigation Project (KRIP) besides the other objectives of Kano City Water Supply (KCWS) and other downstream users. 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. 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.

2.2. Data collection

The water systems under analysis 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). CROPWAT 8.0 was used to estimate the crop water requirement of KRIP and instream flows requirement was assumed. Below are some of the data shown in Table 1.

Table 1 Dry season low in Kano River basin

Flow	Q (Mm^3/s)
Total releases from Tiga reservoir	835.70
Irrigation water requirement in KRIP	206
Kano city water demand	108
In-stream water requirement for Kano River	50

2.3 Monte Carlo Simulation

Monte Carlo simulation was used in this paper. Consider the water allocation problem in Kano River basin involving two principal water users; KCWS and KRIP, each of which receives a benefit, Bi(xit), from the amount of water, xit, allocated to it in each period t. The flows, Qit, at each diversion site i are the random flows Qt less the upstream withdrawals, if any. This situation is shown in Figure 4 for Kano River basin. Monte Carlo simulation can be used to find the probability distribution of the benefits to each user associated with the user's allocation policy.

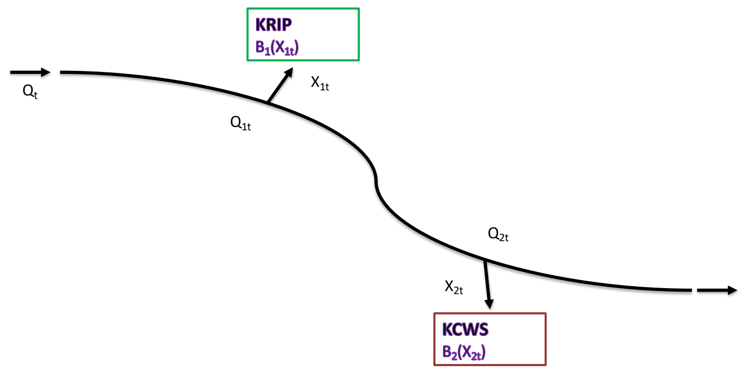

Figure 2 Streamflow allocations in each period t result in benefits, Bi(xit), to each firm i

Suppose the policy is to keep the first 50 units of flow in the stream, to allocate the next 75 units to KNSWB for treatment and distribution to KCWS, and the next 50 units to KRIP. The remaining flow is to be allocated to each of the two users equally up to the limits desired by each user, namely 110 and 210 respectively. Any excess flow will remain in the stream up to the limit of 250 units. Thereafter, the remaining flow to allocate to the users equally.

A simulation model can be created. In each of a series of discrete time periods t, the flows Qt are drawn from a probability distribution. Once this flow is determined, each successive allocation, xit, is computed. Once an allocation is made it is subtracted from the streamflow and the next allocation is made on the basis of that reduced streamflow, in accordance with the allocation policy defined above (its graphical representation is presented in the results section). After numerous time steps, the probability distributions of the allocations to each of the users can be defined. Figure 5 shows a flow chart for this simulation model. Having defined the probability distribution of the allocations, based on the allocation policy, one can consider each of the allocations as random variables, X1 and X2 for KRIP and KCWS respectively.

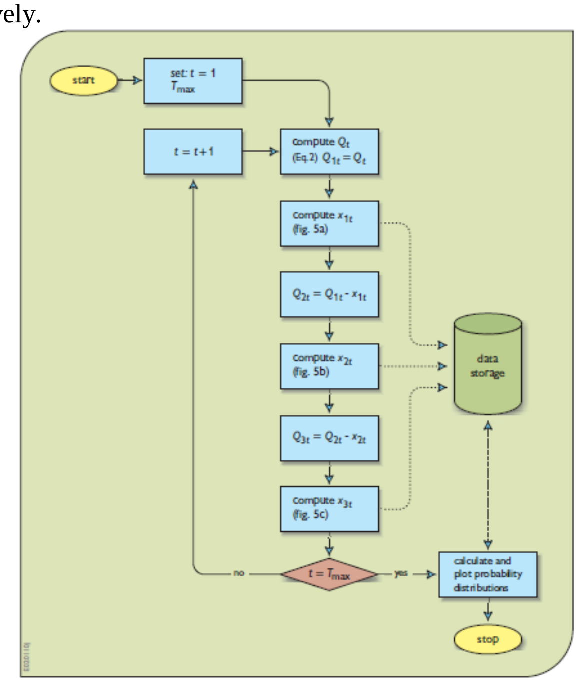

Figure 3 Monte Carlo simulation to determine probability distributions of allocations to each of three water users, as illustrated in Loucks and van Beek (2005). The dashed lines represent information (data) flows

III. RESULTS

A simulation model was created. The initial flow was assumed from no flow (i.e Qt = 0) to the maximum inflow to Tiga dam (850 Mm3) at 50 incrementally. Each successive allocation, xit, was computed by subtracting from the streamflow and the next allocation was made on the basis of that reduced streamflow, in accordance with the allocation policy defined for Kano River basin. Table 2 gives Streamflow allocations in each period to KCWS and KRIP.

Table 2 Streamflow allocations in each period, t, to each user in Kano River basin

QKR1t	XKRIPt	QKR2t	XKNSWBt	Ft
0	0	0	0	0
50	0	50	0	50
100	0	100	50	50
150	0	150	100	50
200	40	160	110	50
250	90	160	110	50
300	140	160	110	50
350	190	160	110	50
400	210	190	110	80
450	210	240	110	130
500	210	290	110	180
550	210	340	110	230
600	225	375	125	250
650	250	400	150	250
700	275	425	175	250
750	300	450	200	250
800	325	475	225	250
850	350	500	250	250

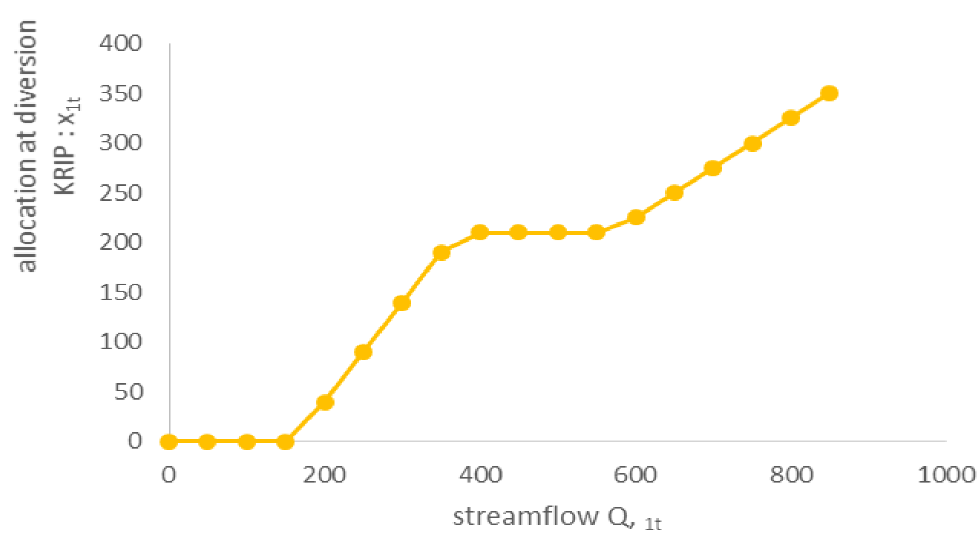

Figure 4 Water allocation policy for KRIP based on the flow at its diversion site.
This policy applies for each period t

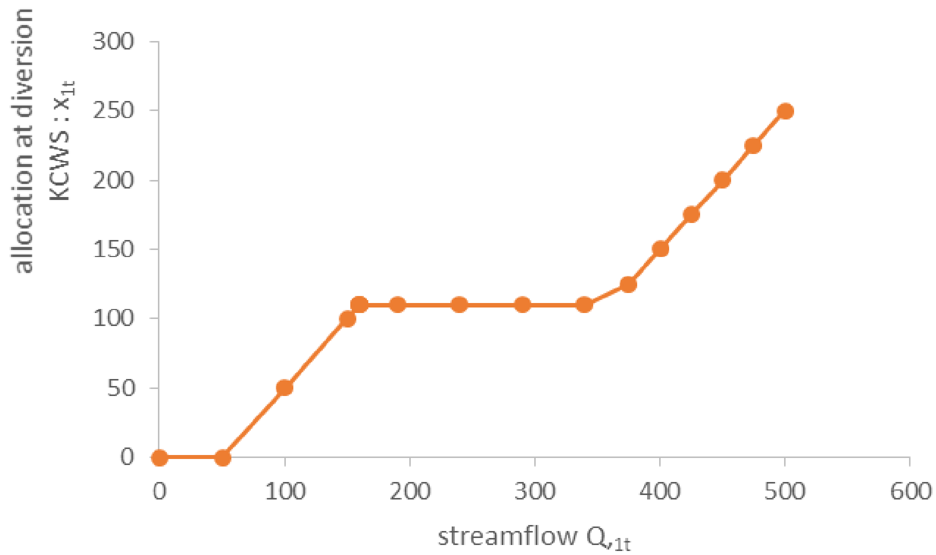

Figure 5 Water allocation policy for KCWS based on the flow at its diversion site. This policy applies for each period t

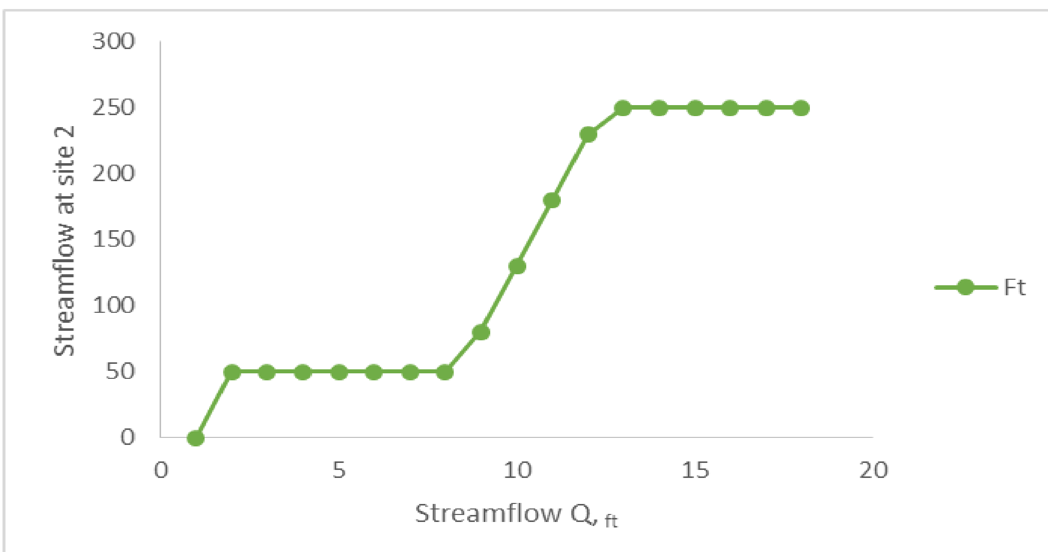

Figure 6 Streamflow downstream of site 2 given the streamflow Q2t at site 2 before the diversion. This applies for each period t

The plots in Figures 4, 5 and 6 illustrate this policy. Each allocation plot reflects the priorities given to the two users and the users further downstream.

IV. CONCLUSION

This paper illustrates the application of Monte Carlo simulation model in Kano River basin and has shown a promising results in that it's capable to simulate under data scarce conditions. The water allocation policy was modelled and now we are in the process of generating probability values using central limit theorem which is going to be used in the model using spreadsheet. Presently, a spread sheet was developed until 20 number for yearly, weekly and daily flows. Future work will constitutes defining the probability distribution of the allocations, based on the allocation policy, consider each of the allocations as random variables, X1 and X2 for KRIP and KCWS respectively.

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