ALLOCATION OF WATER RESOURCES IN SEMI-ARID REGION OF NORTHERN NIGERIA

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ABSTRACT

The uncertainty of water availability and lack of sustainability even when available has challenged the wit of researchers to arrest this menace characteristic of the semi-arid regions. Thus, the best practice globally is to make optimal use of the little but precarious amount of water found in these areas. This study is aimed at achieving optimal water resources allocation in the semi-arid areas using Dadin-Nkowa dam in Gombe State as a case study. A dynamic model was developed based on observed 11-year record of the dam allocation policy to irrigation, industrial and domestic user sectors for each month of the year. The research revealed that only the months with prolonged dry spells achieved optimal returns to the user sectors while the months with records of rainfall could not produce optimized returns in the model. Therefore, the application of the results will lead to saving ₦175, 298,426 annually in the dam provision of water to the region.

KEY WORDS: Model; Optimal; Water Resources; Allocation; Semi-arid Regions

INTRODUCTION

Approximately 30% of total global land area comprises of populated arid and semi-arid areas and water shortages are a major obstacle to social and economic development in these areas. The basic principles for the allocation of water resources are efficiency, equity, and sustainability, with the aims of pursuing the maximum benefit for the society, the environment and the economy, whilst maintaining fair allocation among various areas and people. Sustainable economic development in arid and semi-arid areas depends heavily on sustainable water resource management, defined by Loucks (2000) as "…water resource systems designed and managed to fully contribute to the objectives of society, now and in the future, while maintaining their ecological, environmental, and hydrological integrity." Semi-arid regions are characterized by long, dry seasons and short mild wet seasons. They face periods of water shortages due to high demand and inconsistent supply. Water allocation is often the primary tool of water managers in semi-arid regions (Haten–Moussallen et al, 1999). "Water allocation is a means of dividing up available water resources among multiple users, with an aim of balancing the competing needs for water among all the users" (Australian Department of Agriculture, 2008). Allocation allows limited resources to be shared. In the case of water, allocation is currently made on the basis of whether the resources being assessed is currently in surface storage (surface water) or subsurface (groundwater). Water allocation is based on an estimate of sustainable yield of a defined resource, derived from an understanding of storage capacity, degree of replenishment and the impacts of extraction.

The current practice of water allocation is dominated through administrative mechanism for most rivers. While such a regime may serve to maintain a reasonable equity among different user sectors and areas, many people question the true fairness of this approach because it unintentionally encourages waste and misuse of precious water resource by making water a public good at the basin level. It is against the basic principles of water allocation and production efficiency for maximizing returns on water use. Against the above background, the authors carried out a literature review of modeling studies of water allocation issues and use conflicts management. Broadly speaking, water allocation modeling approaches fall into four categories, i.e. (i) system simulation; (ii) optimum allocation based on optimization theory or economics theory; (iii) optimum allocation based on eco-economics theory; and (iv) optimum allocation based on institutional economics theory. The first approach is optimum allocation based on eco-economics theory. It treats water resource as an element of an integrated nature-society-economy system, aims at maximizing ecological service value or total system ecological benefits with minimum material inputs. The core concept of this method is to minimize the Water consumption Intensity Per unit of Service (WIPS). Based on the comprehensive service capacity of water resources available, one could decide scientifically the levels and limits of the nature-society-economy system development. This approach still lacks of clear theory and detailed rules in its evaluation criteria and research application, and many aspects such as water-eco-environment interactive mechanism and roles of water in the integrated system are being explored. However, there are cases already in which researchers are trying to apply this method in analyzing water allocation and use efficiency issues, e.g. Fu presents a new viewpoint of assessing the value of sustainable water resources development using the so-called marginal ecological utility theory in his Ph.D. thesis (Fu, 2002). The second category of approach is optimum allocation based on institutional economics theory. Such an approach has a broad range of interactive analysis and involves more variables (monitory and non-monitory), and focuses more on integrity and evolution of the issues and influence of regime and rights over market. For water allocation study, it takes into consideration of both traditional factors such as economic, and social system factor. Nevertheless, its application in water allocation study, especially quantitative study, is still at the early stage. Carralo (2005) points out, in his discussions of non-cooperative games model applications, the limitation of negotiation support systems developed by different researchers in solving practical problems, and concluded that negotiation models appropriate are for studying issues of multiple objectives and n-players with incomplete information. Similarly, Wang (2003) provides some preliminary recommendations for improvement of water allocation regime of the Yellow River, on the basis of a qualitative analysis of its historical water allocation regime transformation. This method tackles sustainability of water allocation through analyzing the system stability using game theory. It considers the roles of market, regime and tradition, accommodates the principles of efficiency, fairness and stability by satisfying market, social value and sustainable development requirements in relation to water allocation. The next category which was developed earliest in time is system simulation approach that simulates the pattern, character and essence of prototype water resources system using computer, network and 3S technologies. Examples include the five-reservoir basin model used in the Harvard water resource research program (Maass, 1962), and the water resource model developed by the U.S. Corps of Army Engineers for operational study of cascade reservoirs on the Missouri River (Hall, 1970). Such an approach can vividly present the movement and transformation of water, and is usually used with relatively certain system management rules and regimes. It is however difficult to be adopted in evaluating effectively the water allocation efficiency and regimes.

The fourth category has two varieties: optimization allocation based on theory of optimization; and that based on economics theory, i.e. Pareto optimization theory. The most common approach of the first variety, the linear and dynamic programming model which many scholars worldwide use in analysis of water resources allocation issues, e.g. Institute of Water and Hydropower Research (IWHR) and Tsinghua University in China applied this methodology in solving North China Water Resources Study (Xu, 1997). The second approach is sometimes called marginal analysis method. An example related to the Yellow River is the China Yellow River Basin Investment Planning Study jointly completed by the Ministry of Water Resources and the World Bank using a GAMS-programmed model (The World Bank, 1993). The limitation of the first optimization approach is that it is hard to achieve optimization of an entire system, while that of the second one is that it cannot yet take into account the roles of social factors and assess the impact of regime, planning and tradition, etc. in water allocation, although it can to certain extent assess the efficiency of allocating water as a marketable scare resource. Therefore it is, at the present stage, a comparatively more comprehensive, close to reality, and effective way of representing water allocation related issues. This is the reason why the authors decided to adopt this approach in our discussions and case study. Dynamic programming model, the technique of optimization allocation was utilized in solving water allocation problem in this research. Allocation of water to the various user sectors namely irrigation, domestic and industrial water supply often resulted to conflicts in the chosen case study. This becomes more pronounced in months of dry spell. Hence, this justifies the study by attempting to provide a sharing formula for water allocation in a draught prone area. Thus, the main objective of this thesis work is to determine the optimal allocations to each water demand sector that maximizes the total returns from all the demand sectors – irrigation, domestic and industrial water supply.

THE STUDY AREA

The study area is the Dadin-kowa dam and its environs. This is located at the narrow section of the Gongola River in the present Gombe state, Nigeria. Dadin-kowa dam construction was the Nigerian federal government project. The construction commenced in 1981 and was completed in 1987. It was commissioned by the then head of state: Gen. Babangida in 1988.The dam is a multipurpose project designed to serve among other uses, irrigation, industrial and domestic water supply and flood control. Downstream of the River is located a rice farm that is irrigated by a canal from the dam.According to the farm manager, the farm is a 70Ha land and returns an annual yield of 8.5MT/Ha. The farm is allotted to small farmers cooperatives who pay agreed amount of money to the dam authorities for the water used in irrigation. More than 50 farmers are cultivating on the farmland. There is also a major conduit from the river intake that pumps water to a water treatment plant from where the water is sent to Gombe town for industrial and domestic uses. The water is toll free. In other words, the water board does not charge the users any water rate. The area just like other northern regions of Nigeria has variable rainfall pattern with extreme cases of drought and sporadic flood. It has an average rainfall of 1072.6mm which is suitable for a single wet season crops. Rainfall is usually between the months of July and September unlike the southern part of the country which has a relatively longer period of rainfall. The temperature ranges between 25°C and 34°C. The area is therefore characterized as semi-arid. Most of the rains in the area fall as thunderstorm originating from squall lines. The area has rainfall intensity which normally exceeds the infiltration capacity of the soil. This implies that runoff occurs even without the soil being moist implying that ground water is being replenished.

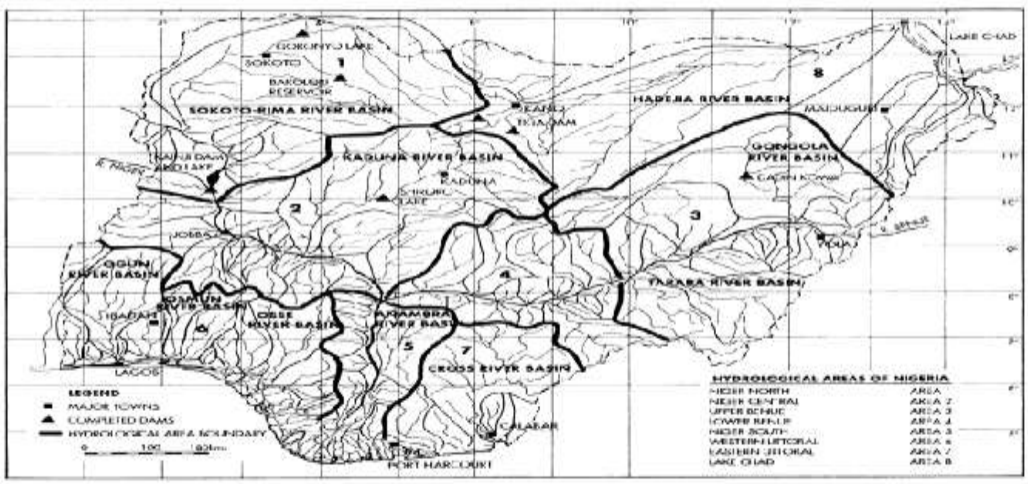

Fig1: Hydrological Map of Nigeria showing the location of Dadin-Kowa Dam

METHODOLOGY

The main data used for the analysis were provided by the Upper Benue River Development Authority, Gombe State, Nigeria. They include information for the period 1991-2001 daily conduit outflow, daily canal outflow, price of water and total daily discharge.

The cash benefits resulting from the use of water for basic house needs such as drinking water, water for cooking, cleaning, laundry, lawn care are referred to as domestic returns. On the other hand, cash returns basically due to allocation of water for various industrial purposes like product processing, cooling of machines, washing of plants and other diverse industrial applications are classified as industrial returns. The allocations from the dam are jointly pumped as town water supply; no separate meters were available to measure allocations to industries and the industries do not have water meters. Thus, industrial and domestic returns were lumped together in the model. The monthly industrial and domestic returns were computed as the product of the price of water, total monthly conduit discharge and the number of days in which the conduit was open in that month. This procedure was repeated for eleven years records of each month. Mathematically,

$$R_1(X_1) = s \times p \times n \qquad (1)$$

where s = Total monthly conduit flow in cubic meters per second (m^3/s),p = price of water in Naira per cubic meter (₦/m^3) and n = number of days the canal was on in a given month.

As stated earlier, the dam allocates water to an irrigation site down stream of the Gongola River. The cash returns resulting from the use of water for irrigation may not necessarily mean the monthly farm yield. This is because the farm yield is a composite unit resulting from more than just water as the farm input. Hence, the returns were computed as the product of the canal discharge, the price of water and the number of days in which the canal was left open in that month. This computation was repeated for eleven years record of the month considered. Mathematically,

$$R_2(X_2) = c \times p \times n \qquad (2)$$

where c = Total monthly canal discharge in cubic meters per second (m^3/s),p = price of water in Naira per cubic meter (₦/m^3) and n = number of days the canal was open in a given month.

MODEL FORMULATION

A consideration of the model formulation for the month of January was first made. Then, the same approach was applied to the other months. However, the constraints for each of the months are different. The constraints for the other months are shown in Table1. For all the months the objective functions and the state variables are the same.

Stage1

State variables: S_1, X_2 , X^*_2 where S_1= Amount of resource (water) available for allotment to agriculture, X_2 = Amount of resource (water) allotted to agriculture and X^*_2 = Allotment to agriculture that results in $F^*_1(s_1)$.

Objective function:

The objective is to maximize the return due to allocation of s_1.

Mathematically:

$$F*_1(S_1) = Max[R_1(X_1)] \quad (3)$$

Constraints:

$0 \leq x_1 \leq s_1$

$0 \leq s_1 \leq 2{,}659{,}651{,}200m^3$

Model:

$$F*_1(S_1) = Max[R_2(X_2)] \quad (4)$$

$0 \leq x_2 \leq s_1$

$0 \leq s_1 \leq 2{,}659{,}651{,}200m^3$

Stage2

State Variables: S_2, X_1, $(S_1\text{-}X_2)$, X^*_1 where S_2 = Amount of resource (water) available for allocation to Agriculture, industrial and domestic uses, X_1 = Amount of resource allocated to industrial and domestic uses, $(S_1\text{-}X_2)$= Amount of resource available for allocation at stage1and X^*_1 = Allocation to industrial and domestic use that results in $F^*_2(S_2)$

Objective function:

$$F*_2(S_2) = Max[R_1(X_1) + F*_1(S_1) - X_2)] \quad (5)$$

Constraints:

$0 \leq x_1 \leq s_1$

$0 \leq s_1 \leq 2{,}287{,}353{,}600m^3$

Model:

$$F*_2(S_2) = Max[R_1(X_1) + F*_1(S_2 - X_1)] \quad (6)$$

$0 \leq x_1 \leq s_2$

$0 \leq s_2 \leq 2{,}287{,}353{,}600m^3$

Table1: Major Constraints in Optimization for Each Month

Month	Stage of programming	Constraints(m^3)
January	2	$0\leq s_2\leq 2{,}659{,}651{,}200$
	1	$0\leq s_1\leq 2{,}287{,}353{,}600$
February	2	$0\leq s_2\leq 1{,}782{,}950{,}400$
	1	$0\leq s_1\leq 1{,}782{,}950{,}400$
March	2	$0\leq s_2\leq 1{,}628{,}467{,}200$
	1	$0\leq s_1\leq 1{,}628{,}467{,}200$
April	2	$0\leq s_2\leq 982{,}022{,}400$
	1	$0\leq s_1\leq 982{,}022{,}400$
May	2	$0\leq s_2\leq 3{,}152{,}563{,}200$
	1	$0\leq s_1\leq 3{,}152{,}563{,}200$
June	2	$0\leq s_2\leq 3{,}983{,}904{,}000$
	1	$0\leq s_1\leq 3{,}983{,}904{,}000$
July	2	$0\leq s_2\leq 5{,}244{,}307{,}200$
	1	$0\leq s_1\leq 5{,}244{,}307{,}200$
August	2	$0\leq s_2\leq 429{,}481{,}440$
	1	$0\leq s_1\leq 429{,}481{,}440$
September	2	$0\leq s_2\leq 679{,}752{,}000$
	1	$0\leq s_1\leq 679{,}752{,}000$
October	2	$0\leq s_2\leq 3.346272\times10^{10}$
	1	$0\leq s_1\leq 3.346272\times10^{10}$
November	2	$0\leq s_2\leq 1.061424\times10^{10}$
	1	$0\leq s_1\leq 1.061424\times10^{10}$
December	2	$0\leq s_2\leq 8{,}991{,}388{,}800$
	1	$0\leq s_1\leq 8{,}991{,}388{,}800$

ASSUMPTIONS

(i) The price of water was assumed to be constant over the years as 1Kobo/m^3. This assumption though not practical was made because water is free of charge in Gombe State.

(ii) Conduit and canal outflows represent allocations to industrial and domestic; agricultural sectors.

(iii) No losses occurred in the allocations to the various user sectors.

(iv) Flow duration in a day was assumed to be 24 hours.

The constraints as well as the results of the parameters estimations are then inputted into the TORA software. The dynamic programming calculations were performed using TORA software. This is a computer program capable of performing calculations in dynamic and linear programming (fig 2 andFig3).

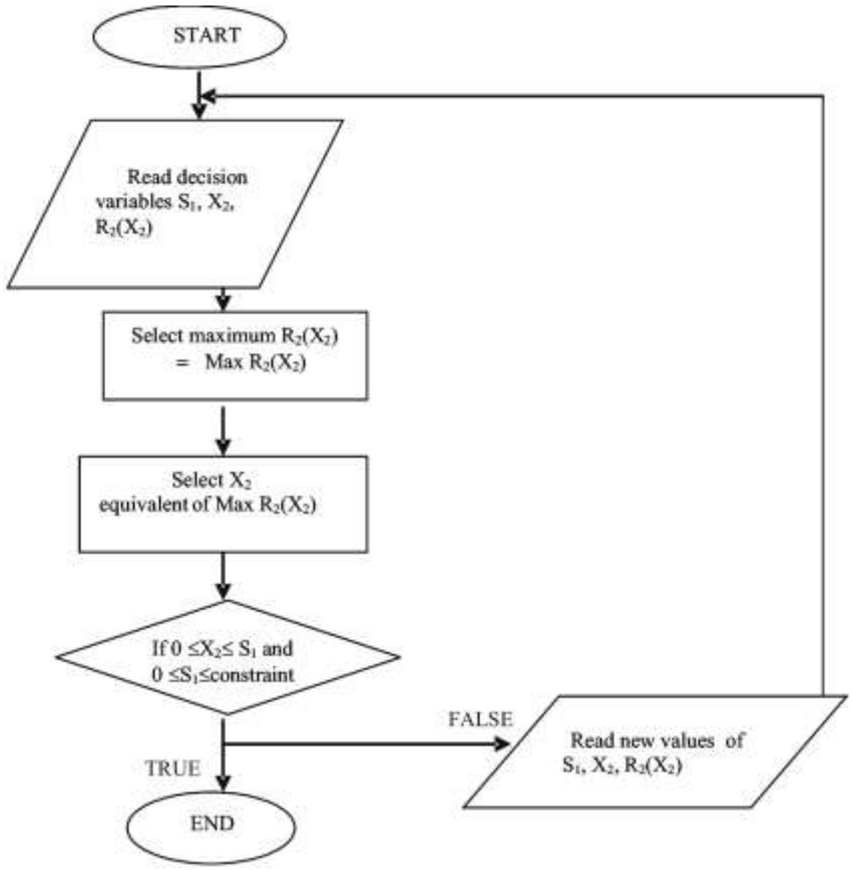

Fig 2: The Algorithm of the Stage 1 Flowchart of the TORA Software Dynamic Programming Calculations.

Table 2b: Summary of the Results for Agricultural Returns

Month	Model Returns x	Real Returns x	Net Savings due to model x
August (1991-2001)	6,642,432	1,555,200	5,087,232
September (1991-2001)	6,220,800	5,812,992	407,800
October (1991-2001)	7,776,000	6,642,432	1,133,568
November (1991-2001)	6,220,880	1,555,200	4,665,680
December (1991-2001)	*	*	*
Total			**17, 019, 018**

* No optimal yield was achieved

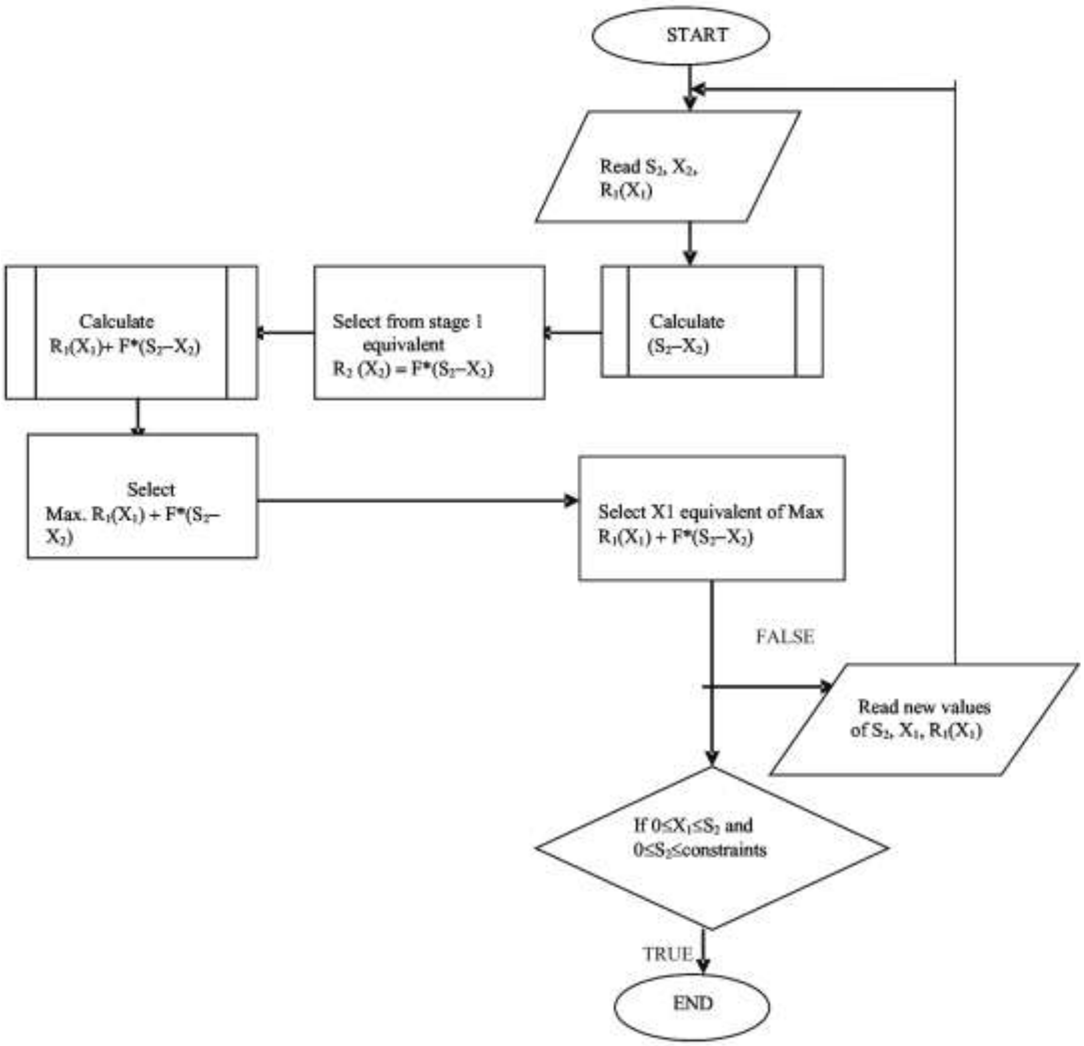

Fig3: The Algorithm of Stage 2 Flowchart of the TORA Software Dynamic Programming Calculations.

RESULTS

Table 2a: Summary of the Results for Agricultural Returns

Month	Model Returns x	Real Returns x	Net Savings due to model x
January (1991-2001)	4,313,088	2,239,486	2,073,602
February (1991-2001)	5,612,544	2,806,272	2,806,272
March (1991-2001)	6,642,432	6,220,000	422,432
April (1991-2001)	*	*	*
May (1991-2001)	*	*	*
June (1991-2001)	*	*	*
July (1991-2001)	6,642,432	6,220,000	422,432

* No optimal yield was achieved

Table 3: Summary of Results for Industrial and Domestic Returns

Month	Model Returns ×	Real Returns ×	Net Savings due to model ×
January (1991-2001)	22,873,536	19,954,080	2,919,456
February (1991-2001)	12,458,000	7,499,520	4,958,480
March (1991-2001)	746,928,000	662,320,640	84,607,360
April (1991-2001)	3,392,062	3,392,064	-2
May (1991-2001)	6,722,784	6,722,000	784
June (1991-2001)	33,410,000	33,410,782	-782
July (1991-2001)	*	*	*
August (1991-2001)	270,920,160	207,847,648	63,072,512
September (1991-2001)	*	*	*
October (1991-2001)	*	*	*
November (1991-2001)	101,088,000	98,366,400	2,721,600
December (1991-2001)	*	*	*
Total			**158,279,408**

* No optimal yield was achieved

From the above, a total of ×175, 298,426 will be saved in the dam annually by using the model.

DISCUSSION

Water is a priceless commodity in the semi-arid regions of the world where irregular rainfall is predominant. Optimization of water allocation is however a tool for ensuring useful application of water. The aim of this study was to determine the optimal returns obtainable in the various months of the year based on 11-year record of water allocation schedule in a dam located in a semi- arid area. Based on the results the following inferences were remarkable. According to the model, optimal returns for various allocations of water: including agricultural; industrial and domestic uses are readily attained in the first three months of the year: January, February and March. Also similar success was recorded in the months of August and November. It could be inferred that optimization of returns to water allocation is possible only the months that have long dry spells, i.e. unavailability of rainfall.September, October; represents periods of partial dry spells, optimal returns were recorded only in the agricultural sector through the use of the model. Thus, partial dry spell favors optimal returns for agriculture.However, the months of April, May, June and December were the zero optimization months as none of the allocation sectors yielded optimal returns for the total unit of water allocated. The model and the real scenario replicated each other in these months. Therefore periods of rainfall do not require any optimization of water allocation based on the above judgments. The functional reservoir volume that supported all allocation policy was observed to be $1.5877557\times10^{10}m^3$ whereas the actual Live storage Capacity of the $1.77\times10^{10}m^3$. Application of the result will lead to saving ×175, 298,426 annually in the dam.

CONCLUSION AND RECOMMENDATIONS

It is strongly recommended that the respective total monthly allocations should never fall below the values presented in the table above. The dam authority is advised to use any of the months of April, May or June for maintenance of the dam facility. This is suggested based on the revelations of the research that no amount of allocations in any of these months would attract any optimal benefit to the water users in any of the demand sectors.

Furthermore, the water allotted to the industrial and domestic sector (town water supply) should be varied within the lower limits of demand especially on days of prolonged rainfall. This is because the energy utilized in pumping the water to the treatment plant as well as the cost of treatment is not justified by the reckless use of the water by the consumers. This is because alternative sources such as rainwater harvesting are available during such days. This recommendation should be followed religiously mainly in the months of July, September, October and December where no optimal returns were observed in the model for industrial and domestic water allocation.

The following allocation policies as shown in the table 4 are recommended for adoption for the management of the Dadin-kowa dam project.

Table 4: Recommended Optimal Allocation of Water

MONTH	RECOMMENDED TOTAL MONTHLY WATER ALLOCATIONS FOR OPTIMAL RETURNS TO ALL SECTORS (m^3)	NUMBER OF DAYS IN THE MONTH	RECOMMENDED AVERAGE DAILY WATER ALLOCATIONS FOR OPTIMALRETURNS TO ALL SECTORS (m^3/s)
January	2,659,651,200	31	993
February	1,782,950,400	29	712
March	873,043,200	31	326
April	982,022,400*	30	975
May	3,152,563,200*	31	1,177
June	3,983,904,000*	30	1,537
July	1,238,976	31	0.5
August	1.6×10^{10}	31	5,974
September	1.6×10^{10}	30	6,173
October	3.3×10^{10}	31	12,321
November	9,830,479,200	30	3,793
December	3,562,272,000*	31	1330

*: current allocation policy which is the average 11-year record for the month.

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