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RESEARCH ARTICLE

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Probabilistic operating rules for Thika Dam in Kenya

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Abstract

Thika Dam, with a storage capacity of 70,000,000 m^3 at full capacity and situated at an altitude of 2041 m above sea level, supplies 84% of the total water used by Nairobi city and its surrounding areas. Since becoming operational in 1994, the dam has been providing water through the Ngethu Water Treatment Plant. Due to rapid population growth in Nairobi and neighboring towns, water demand has risen significantly, leading to the construction of the Northern Collector Tunnel (NCT 1) to augment the dam's inflows. The Kigoro Treatment Plant was also constructed to help meet demand, supplying 1.6 m^3/s, while Ngethu supplies 4.8 m^3/s. To ensure that the reservoir meets the demand and maintains high reliability, the operations are based on policies developed in 2018. However, the 2018 rules were developed based entirely on historical river flows and excluded the Kayuyu River, which contributes 20% of the dam's inflows. Additionally, it was assumed that all the river inflows into the system of the same exceedance probability coincide over time, which is unlikely to happen in practice. This study, therefore, aimed to develop new operating rules that do not have the above-mentioned limitations of the current rules. The rules were developed in four steps: (i) hydrological simulation of the historical river flows for 26 years from 1997 to 2022; (ii) the stochastic generation of 101 temporary-correlated streamflow, rainfall, and

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evaporation sequences using the variable length block bootstrap (VLB) model, each 1000 years long; (iii) multiple monthly short-term (5-year long) system simulations for different decision months and initial reservoir storage states, to obtain 505 stochastic base yields for each combination of decision month and initial storage state; (iv) the use of the base yields to formulate probabilistic operating rules that are considered more robust and more straightforward to use than the current rules.

KEYWORDS

hydrological simulation, probabilistic operating rules, reservoir storage state, stochastically generated streamflow, Thika Dam

1 | INTRODUCTION

The dam operation rules are all the actions that the dam operator must execute to efficiently and safely maintain the dam's main infrastructure and related works, as well as the ordinary operations that must be carried out daily. Different international dam regulations reflect the need for dam operation rules (Egis Bceom International et al., 2018).

Thika Dam, which has a reservoir of 70 million cubic meters storage capacity, has been operational since 1994 and was designed to continuously and reliably meet 84% of the water demand for the residents of Nairobi, Kenya, and its environments. However, since its commissioning, there has been an increase in water demand caused by increased population arising from rural–urban migration and population growth (Egis Bceom International et al., 2018). A comparison of the Nairobi population based on 1989 census data and the most recent 2019 census data shows that there has been an increase of 234% (Kenya National Bureau of Statistics, 2019).

As the world continues to experience climate change, increasing temperature, more variable and changing precipitation, evaporation, streamflow, snowpack, and other factors, the influence on freshwater supply and quality is continually being evidenced. In particular, since 2015, Kenya has been experiencing prolonged dry spells, followed by delayed and below-normal rainfall events, which highly influence the inflows into the Thika Dam (Maina, 2016). Like most cities in the developing world, Nairobi has been experiencing rapid residential developments both in formal and informal sectors, requiring new water supply connections. Unfortunately, Nairobi's water supply is incapable of meeting the fast-growing demand. As a result, the residents face water rationing as Nairobi City Water and Sewerage Company (NCWSC) tries to achieve equitable water distribution. Since 2017, most Nairobi residents have been receiving water a maximum of 3 days a week (Mutono et al., 2022). The latest equitable water distribution program issued in April 2022 shows that most Nairobi residents receive water supply 1 day per week, as depicted in Figure 1 (NCWSC, 2022). As one of the ways of mitigating water shortages in Nairobi with the growing Nairobi population and continued global climate change, which ultimately affects the water inflow into Thika Dam, there is a need to ensure that the Thika Dam reservoir accrues optimal benefits both now and in future.

To improve the performance of complex reservoir systems, planners and managers must identify and assess different designs and operating rules while comparing their projected

EQUITABLE WATER DISTRIBUTION PROGRAMME Reviewed on April 05 2022	
SOUTHERN REGION	
AREA SERVED	**DAY AND TIME**
RIVERSIDE	
Riverside (Ring Road to Chiromo)	Mon Noon to Tue Noon
Riverside (Ring Road to Imperial Bank)	Tue Noon to Wed Noon
Riverside (Imperial Bank to Kirichwa Groove)	Wed Noon to Thu Noon
Riverside (Kirichwa Groove to Riverside 86 Drive)	Thu Noon to Friday Noon
Riverside (Riverside 86 Drive to Riverside lane)	Friday Noon to Saturday Noon
Riverside (Riverside Lane to Germany Embassy)	Saturday noon to Sunday Noon
Riverside (Germany Embassy to Strathmore School)	Sun Noon to Mon Noon
LAVINGTON	
Jacaranda Rd, Muthangari Gardens, Gitanga Rd, Muthangari Close, Vanga Rd	Tue Noon to Fri Noon
Gitanga Rd	Fri Noon to Mon Noon
Upper Kunde Rd	Wed 8.00am to Thu 8.00am
Middle Kunde Rd	Thu 9.00am to Fri Noon
Upper Hedred Rd, Mbaazi Rd, Masanduku Lane, Leloghi Gardens	Fri 9.00am to Sat Noon
Part of Oledume Rd(From Mararo Rd to Oledume Rd and Environs)	Fri 4pm to Sun Noon
Korosho Rd, Lower Hedred Avenue	Sat Noon to Sun 7.00am
Lower Kunde Rd	Sun 8:00 am to Wed 7.00am
KILELESHWA	
Gatundu rd (Between Oleguruoni & Siaya rd)	Mon 9:00 a.m to Tue 12:00
Gatundu rd (Between Gatundu rd/Siaya rd & Kandara rd)	Tue Noon to Wed Noon
Kandara Rd (Min-Supermarket & Gichugu Rd)	Wed noon to Sun 9.00am
Ole Kajuado rd (Min Supermarket & Gichugu rd)	Sun 9:00 am to Mon Noon
Gichugu Rd (Durham rd & Kieni Rd)	Tue Noon to Thur Noon
Mandera Rd, Gem Lane, Dik Dik Lane, Othaya Rd, Kenya High School and Environs	Mon 9:00 am to Sat 9:00 am
Mazeras rd ,parts of Mbooni Rd and parts of Suguta	Sat 12:00noon to Mon 12:00 noon
From Junction of Mugoiri Suguta to Suguta Mazeras.	Mon noon to Tue Noon
Junction of Suguta Mezaras to Junction Suguta Makueni	Thur 12 Noon to Fri Noon

FIGURE 1 The Nairobi County equitable water distribution program issued in April 2022. Source: NCWSC (2022).

performance with the expected objectives. The main approaches for reservoir operation could be classified as optimization-based approaches and probabilistic or stochastic simulation approaches.

The river inflows, catchment rainfalls, and other hydrological fluxes during the future for which the operating rules will be applied are unknown, and approaches that deal with this uncertainty by probabilistically providing ensembles of plausible hydrological data for formulating operating rules are termed probabilistic. Additionally, the water demands, purposes, and objectives the water system serves could vary over time and may not be easily predictable. The probabilistic models try to model the random progressions over time, alternate outputs' time series, and their probabilities (Loucks & van Beek, 2017). The models are used to predict these impacts based on uncertainty assumptions. Numerous stochastic models have been successfully applied in water resources management and planning, including the Monte Carlo simulation, chance-constrained models, Markov processes, and transition probabilities (Loucks & van Beek, 2017).

2 | LOCATION AND DESCRIPTION OF THE THIKA DAM

Thika Dam, also called Ndakaini Dam, is located on Thika River, 100 km north of Nairobi city, in Murang'a county, as shown in Figure 2. Thika Dam is fed by three rivers which are the Thika River, which contributes 50%; the Githika River, which contributes 30%; and the Kayuyu river, which contributes 20% of the total dam inflow. The dam is 65 m high with a 458 m crest length

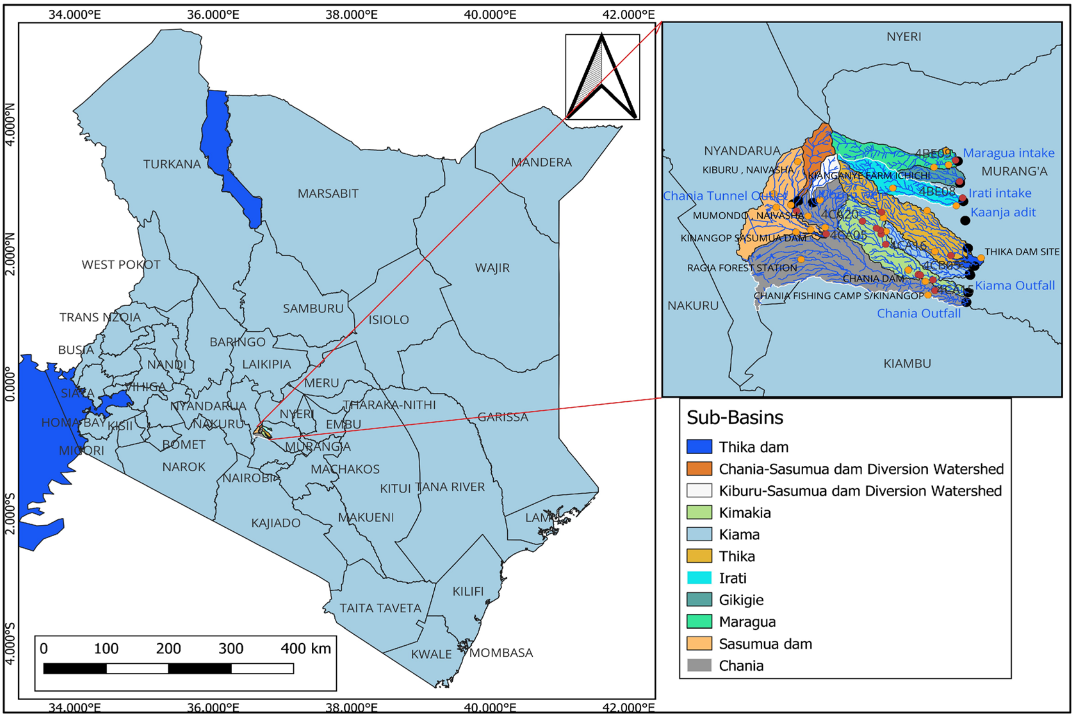


FIGURE 2 The location of the subbasins that contribute water to Nairobi City via Sasumua, Ngethu, and Kigoro water treatment plants.

earth fill dam. The dam has a storage capacity of 70,000,000 m^3 at full storage level at 2041 m above sea level. It produces 430,000 m^3/day of water, about 84% of the total water supply to Nairobi residents and its surroundings (Egis Bceom International et al., 2018).

However, the increased water demand necessitated the construction of the Northern Connector Tunnel (NCT) phase 1 to augment the inflow into the dam. The NCT is expected to increase the Thika Dam reservoir water storage capacity by 138,000 m^3/day or 1.59 m^3/s ((SMEC International Pty Ltd, 2013). The NCT-I is expected to divert water from intakes at the Maragua, Gikigie, and Irati rivers and transfer it through a tunnel 11.6 km long with a 3 m finished diameter and with a capacity of 15.6 m^3/s to the Githika River outfall which then flows to the Thika reservoir. Figure 3 shows the different capacities abstracted from the rivers involved in the Nairobi Water Supply Thika reservoir system and their instream flow requirements.

The water from the dam is supplied through the Ngethu and Kigoro water treatment plants. Water from the dam is conveyed through a system of tunnels running from the dam, tapping the Kiama River and Kimakia River, and diverting the flows to the Chania River at the Chania outfall. The water is then tapped from the Chania River at Mwagu Weir and conveyed via a tunnel to the Mataara chamber, from where it is conveyed by pipelines to the Ngethu water production plant for treatment. From the treatment plant, the water is supplied to Nairobi residents through a gravity conventional system using a 90 km pipeline to Nairobi City, as shown in Figure 4 (Egis Bceom International et al., 2018).

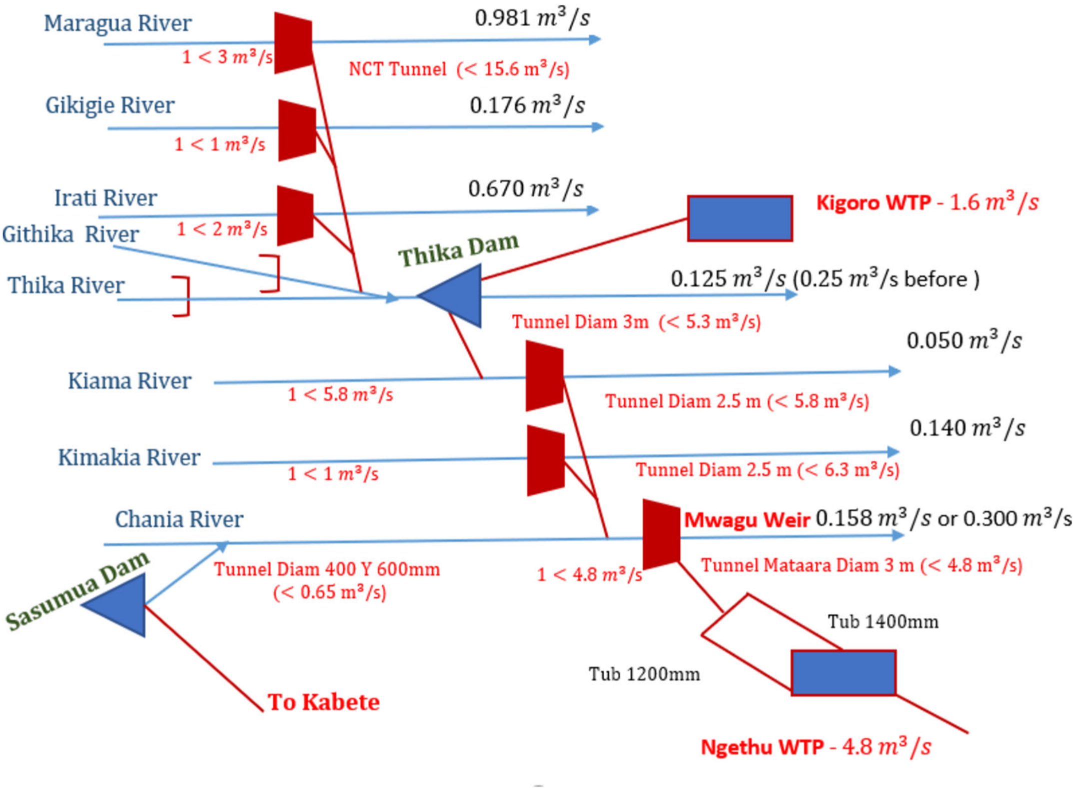


FIGURE 3 Schematic diagram of Nairobi Water Supply from the different rivers in the Thika Chania system, including NCT-1. Source Egis Bceom International et al. (2018).

The inflows into the Thika reservoir system from the Chania River and the diversions from the Kiama and Kimakia Rivers are unregulated. They follow the natural river hydrograph pattern, with the inflows rising during the rainy seasons and falling during the dry seasons. When the inflows from the three rivers are sufficient to meet the demand for Ngethu Water treatment works, no releases are made from the Thika Dam. When there is excess water in the Mwagu weir, spilling is allowed. When the inflows from the three rivers are below the Ngethu water treatment plant demand, releases are done from the Thika Dam to supplement the shortfall in the run of the river inflows. The required releases from the Thika Dam are determined by observing the water level in the Mwagu weir (Egis Bceom International et al., 2018).

3 | THE 2018 THIKA DAM OPERATION RULES

Thika Dam operation rules were established in August 2018 as an update of the Operation Manual of the Thika reservoir, which the Nairobi City Council had established in August 1996 (Egis Bceom International et al., 2018).

As of October 2023, the water demand in Nairobi was 9.375 m^3/s, and the Thika Dam system was expected to meet 84% of Nairobi's water supply through Ngethu and Kigoro treatment plants (AWWDA, 2022). This was achieved by supplying 6.4 m^3/s, 4.8 m^3/s to Ngethu and 1.6 m^3/s to the Kigoro plant.

The 2018 Thika Dam operation rules were established by analyzing the probability of exceedance of flows in which the system is located. This was achieved by first determining the contributions of the rivers in the system and the water supply demands for Nairobi. Analyses of the available maximum levels/volumes to meet the demand were then done, followed by calculation of the exceedance probabilities using the historical hydrological data of the main subsystems of the system, which are Mwagu Weir (Chania, Kiama, and Kimakia rivers), Thika River (at the confluence of Thika and Githika rivers), and Northern Collector I (Maragua, Gigikie, and Irati rivers) (Egis Bceom International et al., 2018).

The following are the 2018 rules followed for operating Thika Dam (Egis Bceom International et al., 2018):

1. The flow passing through the Chania River at the Mwagu weir is first measured.

Then, establish the exceedance probability zone where the water level in Mwagu Weir lies. The exceedance probability (Pexc) zones are as follows and as shown in Figure 5:

- Zone 1 - $\text{Pexc} \leq 70\%$
- Zone 2 -$70\% < \text{Pexc} \leq 90\%$
- Zone 3 -$90\% < \text{Pexc} \leq 95\%$
- Zone 4 - $\text{Pexc} > 95\%$

Once the zone is established, a vertical line is drawn based on the month of the year on the graphic representation of the zones.

2. The water level of the Thika reservoir is then measured. The level measured is then plotted on the corresponding graphic on the horizontal axis.

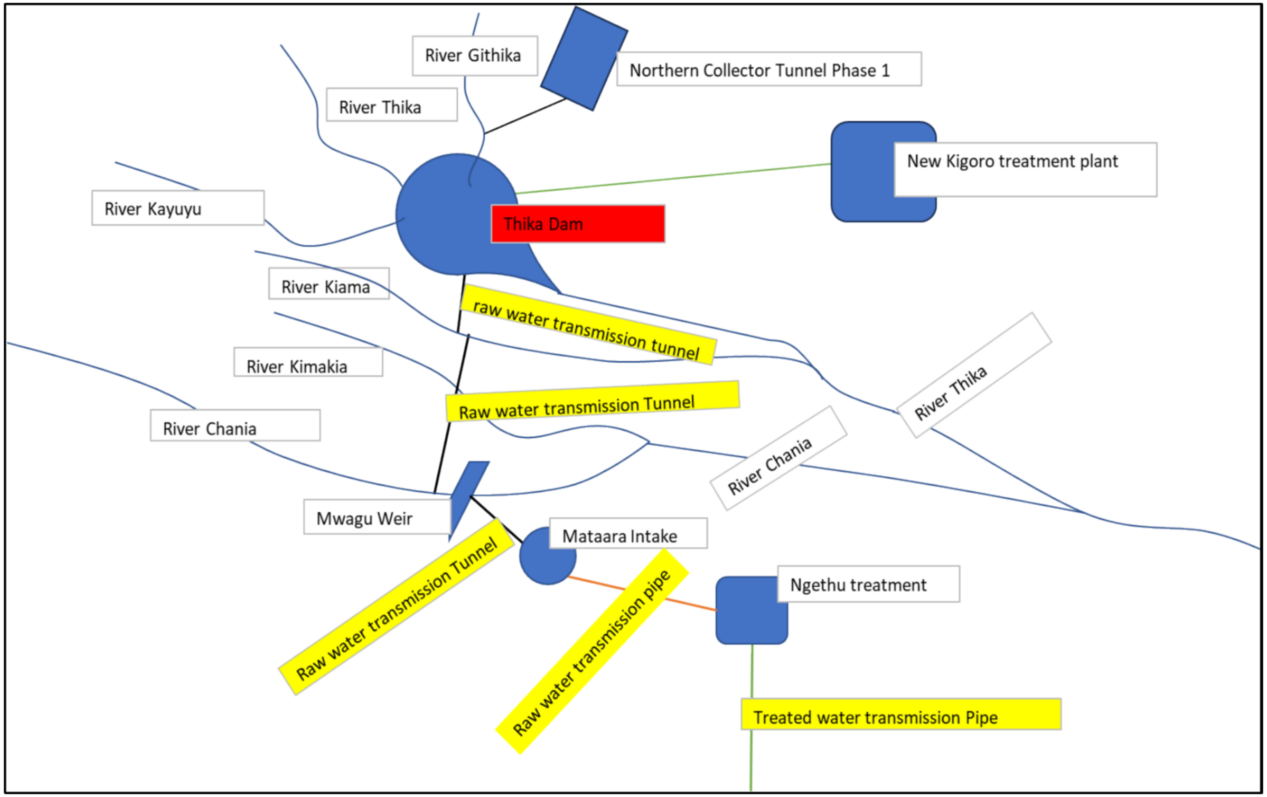


FIGURE 4 A schematic diagram of the Thika–Ngethu system.

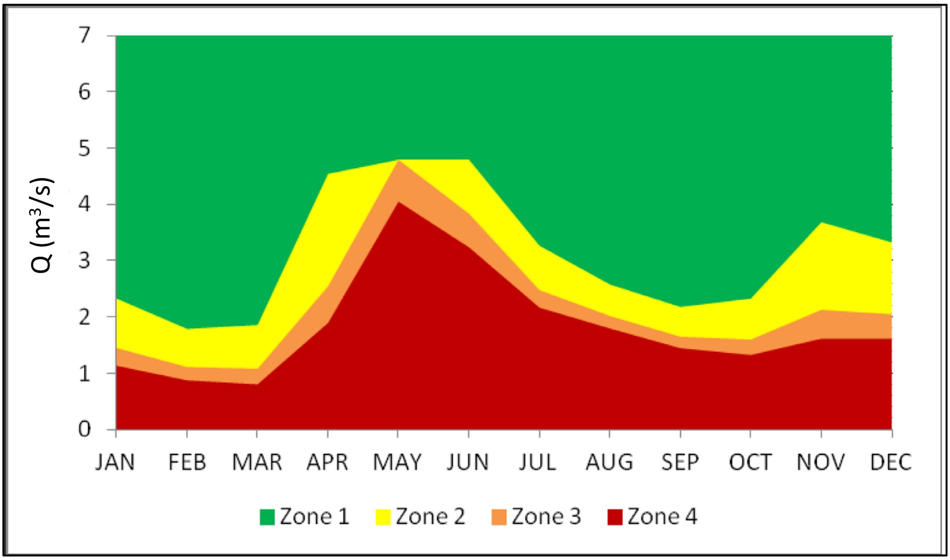


FIGURE 5 Exceedance probability zones at Mwagu weir. Source: Egis Bceom International et al. (2018).

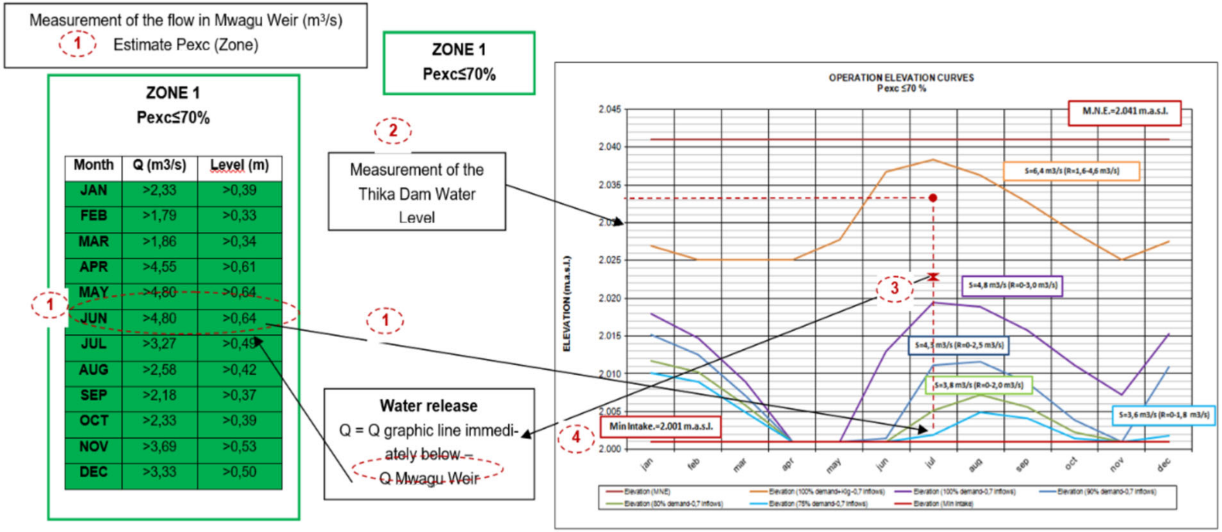
The point at which lines drawn from the Thika Dam water level and Mwagu weir water level meet represents the reservoir conditions shown in Figure 6.

3. The flow necessary for supply is then established by drawing a vertical point to the nearest line below from the point of intersection established prior, as shown in Figure 6.
4. The water released from the reservoir is equal to the supply represented on the graph by the line below the point of intersection, less the discharge measured at Mwagu weir.

Figure 7 shows the summary for the with Northern Collector phase I operation rules under normal conditions (Egis Bceom International et al., 2018).

3.1 Gaps identified in the 2018 Thika Dam operation rules

1. The rules to guide the future operation of Thika Dam were established based on the historical river flows. However, historical river flows provide data for flows that happened in the past, and future flows are unlikely to be the same as historical ones.
2. During the development of the 2018 operation rules when calculating the exceedance probability for the reservoir, the Thika Dam primary inflows were considered to be from the Thika and Githika rivers only. However, the Thika Dam's primary inflows are usually 50% from the Thika River, 30% from the Githika River, and 20% from the Kayuyu River. The omission of Kayuyu River's inflow, which forms 20% of the dam inflow during the calculation of the probability of exceedance, ultimately affects the overall likelihood of exceedance.
3. In the development of the 2018 operation rules, it was assumed that at the time of modeling, all the system rivers' contributions with the same exceedance coincide over time. However, the exceedance probabilities are unlikely to be co-incidental in reality for all the inflows involved; Chania, Kiama, and Kimakia rivers supplying Mwagu Weir, and Maragua, Gigikie, Irati, Githika, and Thika Rivers supplying Thika Dam.



Month	Q (m3/s)	Level (m)
JAN	>2,33	>0,39
FEB	>1,79	>0,33
MAR	>1,86	>0,34
APR	>4,55	>0,61
MAY	>4,80	>0,64
JUN	>4,80	>0,64
JUL	>3,27	>0,49
AUG	>2,58	>0,42
SEP	>2,18	>0,37
OCT	>2,33	>0,39
NOV	>3,69	>0,53
DEC	>3,33	>0,50

FIGURE 6 Example of operation curves for July for Mwagu water level within in zone 1. Source: Egis Bceom International et al. (2018).

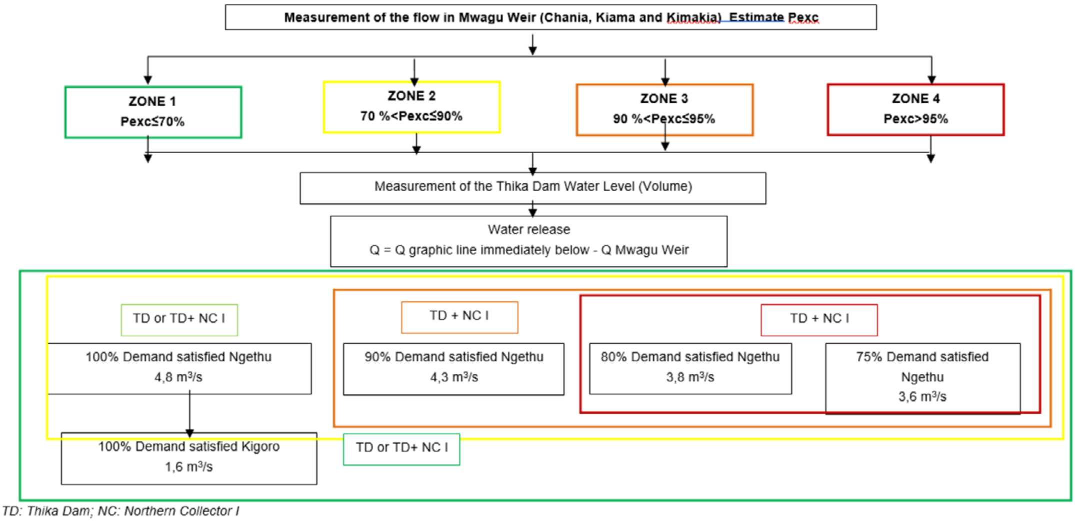


FIGURE 7 Summary of Thika Dam with NCT I operation rules. Source: Egis Bceom International et al. (2018).

This study aimed to develop operating rules for the system that effectively address the gaps listed above.

4 | DATA

4.1 | Meteorological data

Historical meteorological data for the Thika Dam upstream subbasin and the associated subbasins whose rivers contribute to the inflows of the Ngethu water treatment plant were required for river flow simulation. The required meteorological data include rainfall data and evapotranspiration data. The subbasins that were included in the study are shown in Figure 8, and the primary subbasins inflowing to Thika Dam are shown in Figure 9; they include the following:

- Thika Dam subbasins, as shown in Figure 9, are:
  - Thika River subbasin upstream of Thika Dam
  - Githika River subbasin upstream of Thika Dam inlet
  - Kayuyu River subbasin upstream of Thika Dam inlet
- Thika–Chania tunnel subbasins, which are:
  - Kiama River subbasin upstream of the inlet to the Thika–Chania tunnel
  - Kimakia River subbasin upstream of the inlet to the Thika–Chania tunnel
  - Chania River subbasin upstream of the inlet to the Thika–Chania tunnel
- Northern Collector Tunnel Phase I subbasins, which are:
  - Maragua River subbasin upstream of the inlet to NCT I
  - Gikigie River subbasin upstream of the inlet to NCT I
  - Irati River subbasin upstream of the inlet to NCT I

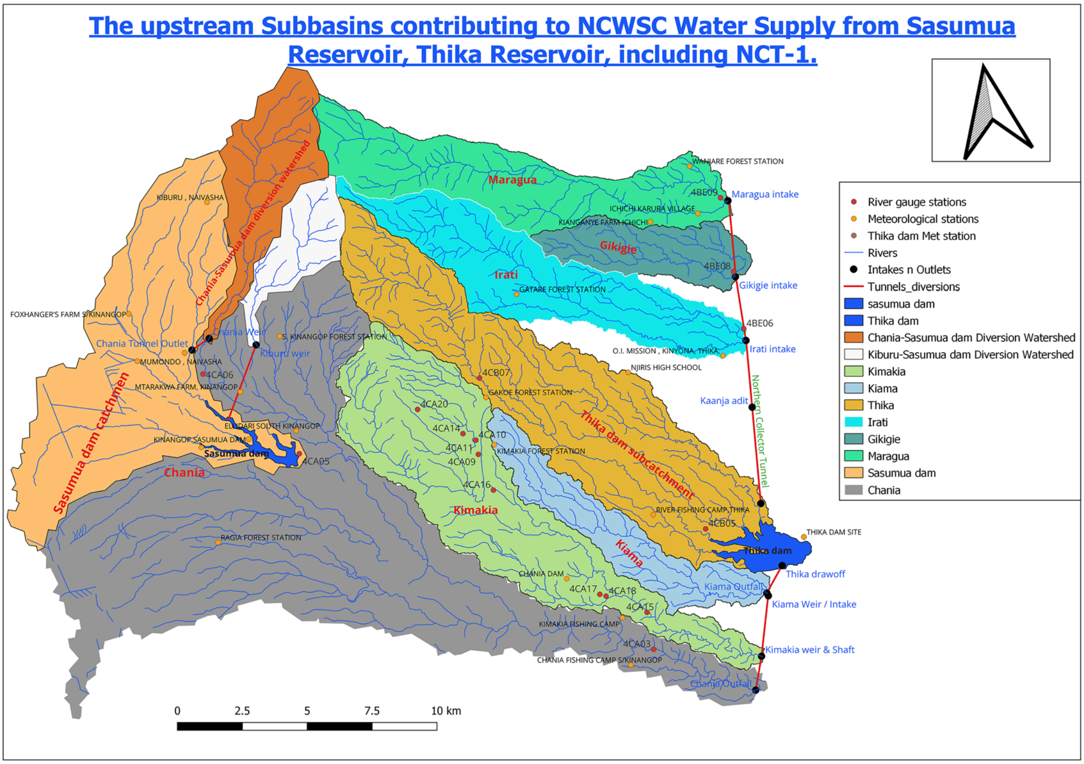


FIGURE 8 The upstream subbasins contributing to NCWSC Water Supply from Sasumua Reservoir, Thika Reservoir, including NCT-1.

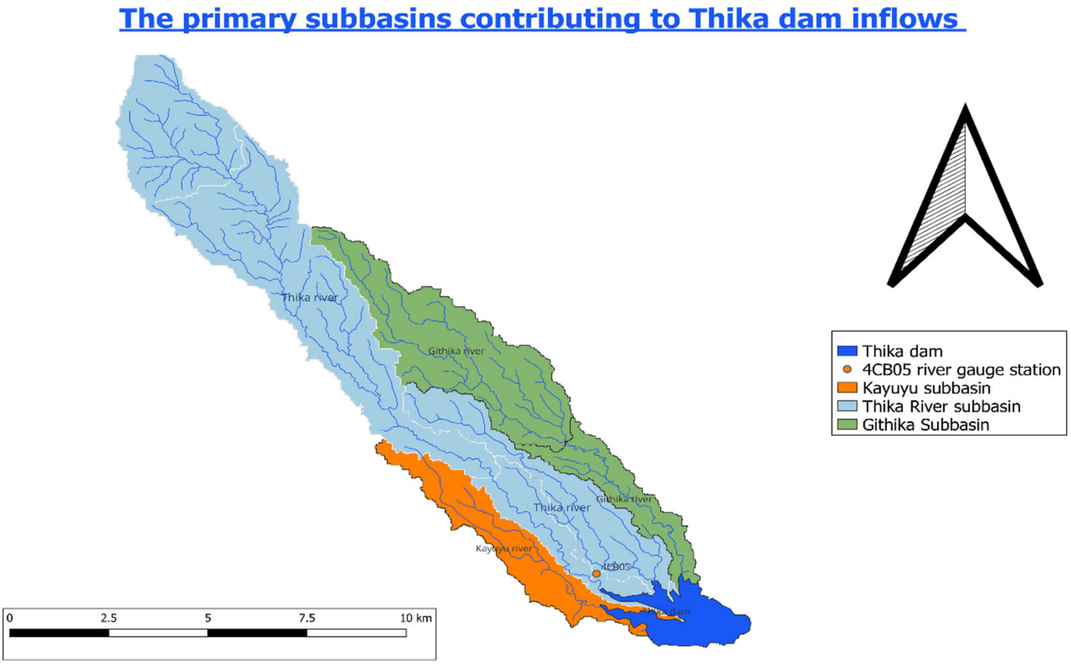


FIGURE 9 The primary subbasins contributing to Thika Dam inflows.

The historical observed rainfall, temperature, and evapotranspiration data were acquired from the Thika Dam Site station, managed by the NCWSC Thika Dam team and Kenya Meteorological Department. The data period was between January 1997 and December 2022. The Thika Dam weather station is located on the lower side of the upstream subbasins under study, as shown in Figure 8.

Most of the subbasins within the study area did not have meteorological stations with the data that was required. The observed rainfall data for the subbasins draining into the dam was obtained by increasing the Thika Dam weather station's observed rainfall data by 12%. The 12% was obtained by comparing the Thika Dam meteorological station observed data with the Kimakia and Gatare forest weather station observed data, whose climatic conditions are similar to the subbasin area inflowing to Thika Dam upstream of the dam inlet. For the rest of the subbasins other than the Thika Dam upstream subbasins, the rainfall data used in the study was satellite data, which had been corrected using yearly- monthly correction factors (Climate Hazard Group, 2018). The annual monthly correction factors were obtained by comparing Thika Dam weather station observed rainfall data and Chirps 4.8 km daily data (1997–2022) for the Thika Dam weather station location.

The evapotranspiration data used for all the subbasins was satellite data, i.e., ASCE Grass Reference Evapotranspiration (ETo) data from MERRA2-50 km daily (GMAO, 2015). The simulation was done from 1997 to 2022 because the Thika Dam met station rainfall data available to calculate the correction factors for satellite data ranging between 1997 and 2022.

4.2 | Discharge data

At the time of request of historically observed river discharge, out of the 9 rivers in the study area, the only streamflow data available was for Thika River, recorded at river gauge station 4CB05 from 10/06/1950 to 01/31/2005. The Thika river discharge was obtained from the Water Resource Management Authority (WRA) database. Notably, the discharge data from 4CB05 had considerable gaps, with 77% of the data missing. For the rest of the rivers whose observed discharge data was missing, river gauges were installed previously, but they had been vandalized.

5 | HYDROLOGICAL SIMULATION

The hydrological simulation was done for the Thika, Githika, and Kayuyu rivers to determine the historical inflows to the Thika Dam, Kiama, Kimakia, and Chania Rivers to determine the historical inflows to Thika–Chania system and Maragua, Gikigie and Irati rivers to determine the historical NCT-1 inflow into Thika Dam. The simulation used the GR4J model, which belongs to the family of airGR models developed by the French National Research Institute for Agriculture, Food, and the Environment (INRAE) (Coron et al., 2023).

GR4J is a lumped rainfall-runoff conceptual model that has proven to be efficient in reproducing river discharges based on previous studies, owing to its easiness, little data requirements, and being freely available (Coron et al., 2023).

The model was calibrated using the observed Thika River discharge data from January 1, 1997, to January 31, 2005, and validated using the Thika River 1950 to 1997 data. For all the subbasins, the simulation was done for the period between January 1, 1997, to December 31, 2022. The simulation was done by writing the codes using R studio. It included setting up

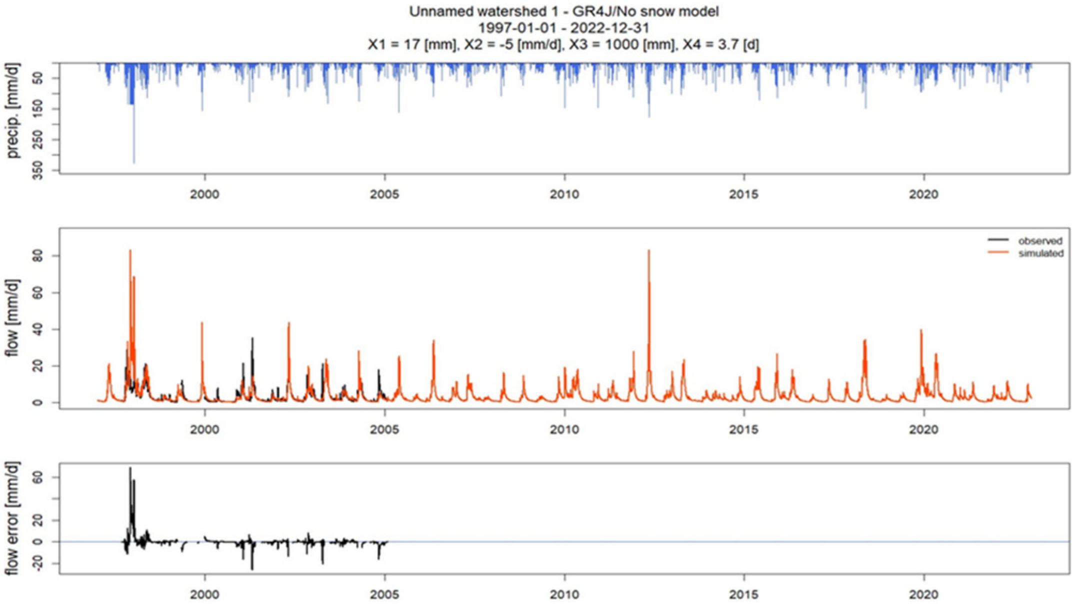


FIGURE 10 Flow time series of Thika River watershed upstream of RGS 4CB05.

the working directory, loading the observed data, checking for missing data, conversion the date column to UTC format, and calibrating the model using the January 1, 1997, to January 31, 2005, observed discharge data with January 1, 1996, to December 31, 1996, as warm-up period, and simulation of discharge data from January 1, 1997, to December 31, 2022, using the precipitation and evapotranspiration data using the ShinyGR function. Figures 10 and 11 show the flow time series simulation and the GR4J Model performance of the Thika River watershed upstream of RGS 4CB05. Table 1 shows the summary of variables used and the result from the simulation of the subbasins under study.

6 | DEVELOPMENT OF OPERATING RULES

The development of operating policies involved the formulation of rules that help in deciding the amount of water available for allocation to the various demands for a year starting from a decision date, which is frequently the end of the rainy season. In addition, the rules allow additional decisions to be made within the year if the changes have been observed in storage.

The rules were developed in three steps. First, stochastic data generation to adequately incorporate statistical reliability into the development of the rules was done using the variable length block bootstrap (VLB) model (Ndiritu, 2011). Second, multiple short-term system simulations were done to obtain a large ensemble of probable system performance. Lastly, the results of the numerous simulations were used to formulate the operating rules.

6.1 | Stochastic data generation

The historical river flows provide data for flows that happened in the past, and it is highly improbable that they will be the same in the future. Therefore, when historical sequences are

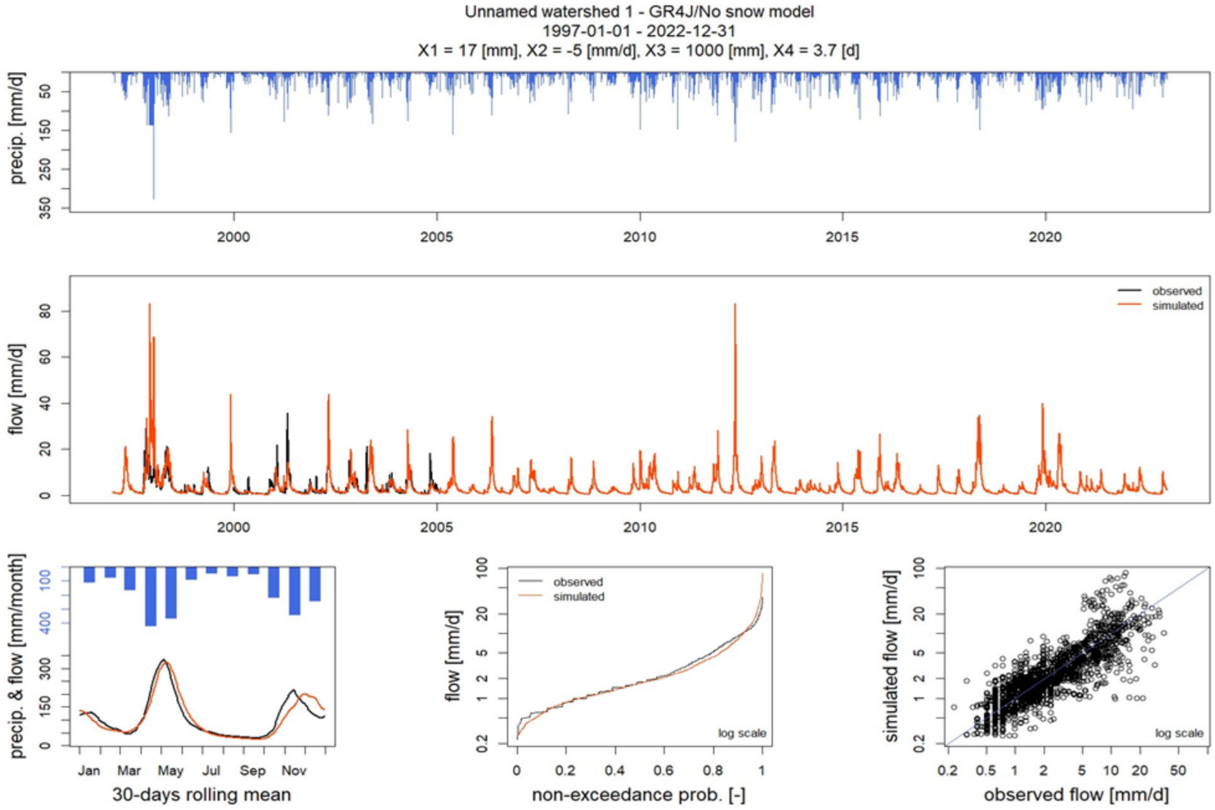


FIGURE 11 GR4J model performance for the simulation Thika River watershed upstream of RGS 4CB05.

TABLE 1 Hydrological simulation data inputs and output for the Thika reservoir system subbasins.

Subbasin	Total upstream area (km^2)	Area contributing to inflows into the Thika–Chania system (km^2)	Historical rainfall mean (mm/day)	Historical ETP mean (mm/day)	Simulated inflows mean (m^3/s)	Data period
Total Thika Dam inflow (Thika, Githika, and Kayuyu rivers)	68.02	68.02	6.02	4.29	2.829	1997–2022
Kiama	20.12	20.12	5.325	4.288	0.804	1997–2022
Kimakia	56.87	56.87	5.332	4.288	2.340	1997–2022
Chania	247.78	140.78	5.127	4.289	5.398	1997–2022
Maragua	37.39	37.39	4.769	4.289	1.286	1997–2022
Gikigie	14.85	14.85	4.768	4.289	0.526	1997–2022
Irati	36.15	36.15	5.043	4.289	1.358	1997–2022

used to study the future performance of the reservoir, they do not adequately incorporate the uncertainties involved (Ndiritu, 2011). Therefore, several stochastically generated sequences were applied to study future reservoir performance to incorporate statistical reliability. For the synthetic sequences to be considered adequate for use in reservoir study, they must meet the following requirements:

1. The statistical properties of individual and joint synthetic sequences must be similar to the historical sequences.
2. The synthetic sequences must pass the validation tests.

The VLB method (Ndiritu, 2011) was applied, and a nonparametric multisite monthly stochastic generator (Ndiritu, 2011) was previously developed and tested using South African streamflow data.

The VLB starts by creating blocks of historical data of variable length and randomly selecting them with replacements to create the initial synthetic sequence of yearly flows of the required length. The bias that could have been created by each block starting with a wet period is removed during the sequencing process by providing a warm-up period of 20 years. The stochastic sequence of the specified size is then achieved by locating the initial year randomly amongst the first and the 20th year, thus avoiding bias. The contemporaneous approach that maintains annual spatial cross-correlations (Srinivas & Srinivasan, 2001, 2005) has been adopted for the VLB and found to be effective. Every historical sequence is alternately used as the lead sequence to acquire a stochastic sequence of yearly flows for all the other sequences (multiple sites) to enable this. Using every historical sequence as the lead sequence an identical number of times prevents the generation of sequences that could be biased to only one site (Ndiritu, 2011).

Thika reservoir's maximum normal elevation (MNE) is set at 2041.00 m a.s.l., with its total volume accumulating to 69.46 Hm^3. The Thika reservoir has a live storage of 63.68 Hm^3, which ranges between level 2001.00 to 2041.00 m a.s.l. The minimum allowed reservoir water storage is 5.78 Hm^3 (Egis Bceom International et al., 2018). The Thika Dam was considered to receive inflow primarily from the Thika, Githika, and Kayuyu rivers, with additional inflow from NCT-1, which collects water from the Maragua, Gikigie, and Irati rivers through the Githika outfall.

The Thika Dam is expected to supply water to Nairobi through Ngethu and new Kigoro treatment plants. The demands of Nairobi city water provided from the Thika reservoir were assumed to be constant throughout the year. They were estimated at 4.8 m^3/s for the Ngethu plant and 1.6 m^3/s for the Kigoro plant, giving a total demand of 6.4 m^3/s. For the formulation of the operating rules, it was required to apply a range of target drafts, and the range of 1 to 10 m^3/s was selected for this. For each target draft, the proportion of the demand assigned to Ngethu and Kigoro was set as the proportion of the demands to the two plants: 75% to Ngethu and 25% to Kigoro treatment works. In addition, the environmental flows of the rivers contributing to the inflows of the Thika–Ngethu system, including NCT-1, were also considered as an additional demand. Table 2 summarizes variables for the rivers contributing to the Thika–Ngethu system, including NCT-1.

The VLB stochastic generator was used to generate 101 stochastically generated streamflow sequences, each 1,000 years long, using the 26-year historic inflow time series obtained from flow hydrological simulation (Section 5 of this paper). The rainfall and evaporation sequences were also stochastically generated for 1000 years using the 26 years of historical data for the Thika reservoir water balance. The following historical data sets ranging from January 1, 1997, to December 31, 2022, were utilized as inputs for the stochastic generator:

- Thika Dam observed precipitation data from the Thika Dam weather station.
- Thika Dam evapotranspiration data was obtained from MERRA2-50 km daily (GMAO, 2015).
- Simulated Thika Dam inflow: the total inflow from the Thika, Githika, and Kayuyu rivers
- Simulated Kiama River inflows to the Thika–Chania system
- Simulated Kimakia River inflows to the Thika–Chania system
- Simulated Chania River inflows to the Thika–Chania system
- Simulated Maragua River inflows to NCT 1
- Simulated Gikigie River inflows to NCT 1
- Simulated Irati River inflows to NCT 1

TABLE 2 Variables for rivers contributing to the Thika–Ngethu system, including NCT-1.

	River	Average inflow (m^3/s)	Environmental flow (m^3/s)	Intake capacity (m^3/s)	Tunnels capacity (m^3/s)
Thika Dam inflow	Total Thika Dam inflow	2.829	0.125	5.3	5.3
Thika–Chania system	Kiama	0.802	0.05	5.8	5.8
	Kimakia	2.334	0.14	1	6.3
	Chania	5.388	0.158	4.8	4.8
NCT-1	Maragua	1.283	0.981	3	15.6
	Gikigie	0.525	0.176	1	15.6
	Irati	1.356	0.67	2	15.6

The stochastic model generated only 101 sequences for each data set, which was considered low for exhaustive statistical analysis. Therefore, for every decision month, 505 5-year-long stochastic sequences were obtained from the 101 1000-year-long sequences with a gap of a minimum of 10 years in between to ensure that the sequences are independent.

6.2 | Formulation of the operation rules

Considering that future dam inflows over the operational period and the climate variability are unknown, the probabilistic method was applied to obtain operating policies that sufficiently specify the reliabilities linked to the water allocation choices.

The operating policies were established from statistical analysis of the base yields from 505 simulations of the integrated Thika reservoir, Thika–Chania system, and NCT 1 (Figure 8), each with 5-year-long stochastically generated inflow sequences and Thika reservoir rainfall and evaporation.

The base yield, considered the minimum yearly yield, was obtained for every 5-year sequence by monthly simulation of the reservoir for five different starting storage states, which were 100%, 60%, 40%, 20%, and 10% of the total reservoir storage. In addition, annual target drafts/demands varying between 0 and 10 m^3/s were applied. For all the starting storage states, the minimum allowed storage state was set at 5.78 million cubic meters, which is 9.1% of the Thika reservoir's live storage capacity. This process was done with 4 different decision months: March, June, September, and December.

The 505 base yields obtained at every starting storage state and target demand were then ranked, and the probability that any specified base yield is not exceeded during the 5 years was calculated using the Weibull plotting position formula, as shown in Equation (1).

$$P_{n,5} = \frac{m}{n+1} \tag{1}$$

where m is the rank of the base yield, the lowest of all the base yields was ranked as 1, n is the total base yield, which is equivalent to 505, and $P_{n,5}$ is the probability that the base yield has not been exceeded during the 5 years (Ndiritu et al., 2017).

The probability of the base yield being surpassed in any of the years and the corresponding return period were then calculated. The likelihood of each base yield being exceeded in any year was considered $P_{e,1,}$ while the probability of this base yield not being exceeded in any year is $1 - P_{e,1}$. Assuming that the non-exceedance probabilities are independent, the product of these probabilities for 5 years is equivalent to the likelihood that the base yield is not surpassed over the continuous 5-year period, as shown in Equation (2) (Ndiritu et al., 2017).

$$(1 - P_{e,1})^5 = P_{n,5} \tag{2}$$

The annual recurrence interval r_i of exceedance of the base period is calculated using Equation (3).

$$r_i = \frac{1}{P_{e,1}} = \frac{1}{1 - P_{n,5}^{\frac{1}{5}}} \tag{3}$$

Figures 12 and 13 show the relationship between the base yield and return period for different initial storage states of 10% and 100% for the decision months of March and June, respectively, for various target drafts.

From the base yield–return period–initial storage state relationships, the relationships between the recurrence interval and target drafts for the different initial storage states of 10%, 20%, 40%,60%, and 100% were established. Figures 14 and 15 show the curves obtained from relationships between the return period and target drafts for the decision months of September and December.

The return period–target draft curves are then used to get the storage state-target draft curves for specific return periods, which guide the maximum yearly demand that can be met at the particular storage state of the reservoir. The curves were done for the 4 decision months for recurrence intervals of 1 in 100, 1 in 50, 1 in 10, 1 in 5, 1 in 4, and 1 in 2.5, as shown in Figures 16 and 17. The recurrence intervals are guided by the supply reliabilities shown in Table 3.

Based on the storage states–target draft curves established for different return periods, it was shown that the Thika Dam system, including NCT 1, cannot meet the total demand of 6.4 m^3/s at all times. The 6.4 m^3/s can only be met in the 4 decision months with a low reliability of 60% (1 in 2.5 years), as shown in Figures 14 and 15. However, a high level of assurance is required to meet the demand for water supply. Therefore, from the storage states–target draft curves for different return periods, the operation rule curves of the dam were obtained from the storage states–target draft curves for 98% reliability, that is, 1 in 50 return period, and 90% reliability, that is, 1 in 10 return period as shown in Figures 16 and 17. Linear interpolation was applied to establish the storage states for the other months not included in the stochastic simulations.

The operation curves shown in Figures 18 and 19 are expected to guide the dam operators on how much water can be released to meet the Ngethu and Kigoro plants' demand. The

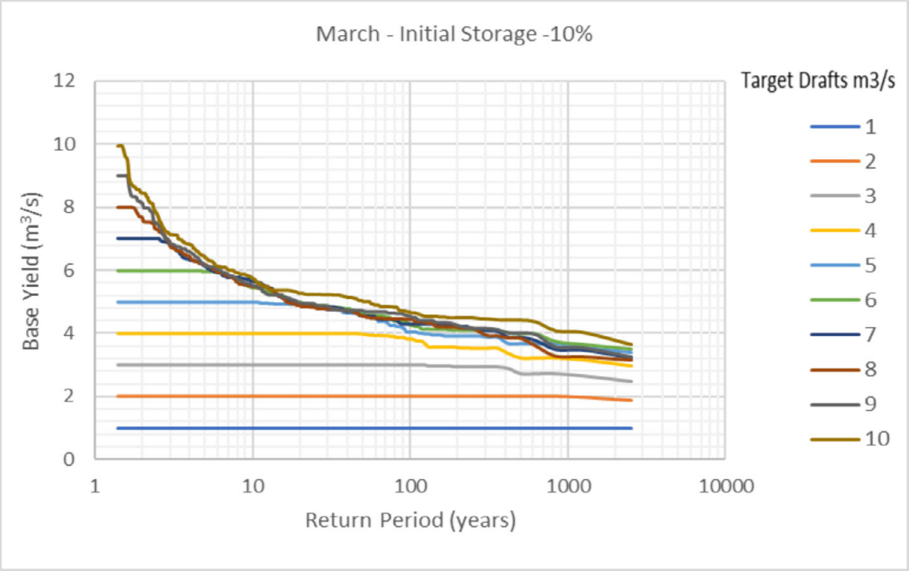


FIGURE 12 Base yield–return period–initial storage state 10% for March.

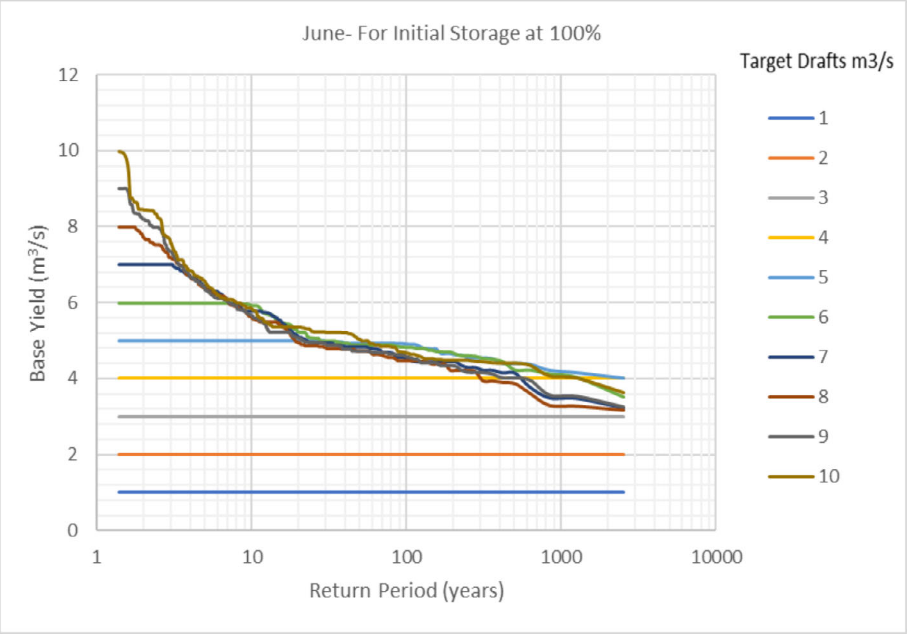


FIGURE 13 Base yield–return period–initial storage state 100% for June.

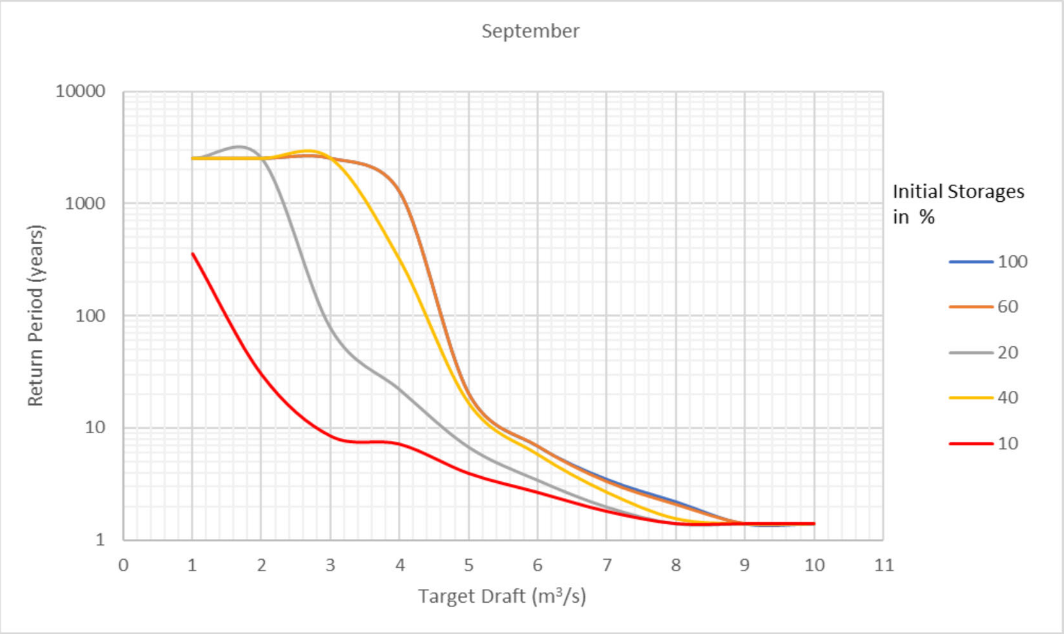


FIGURE 14 Return period–target draft curves for September.

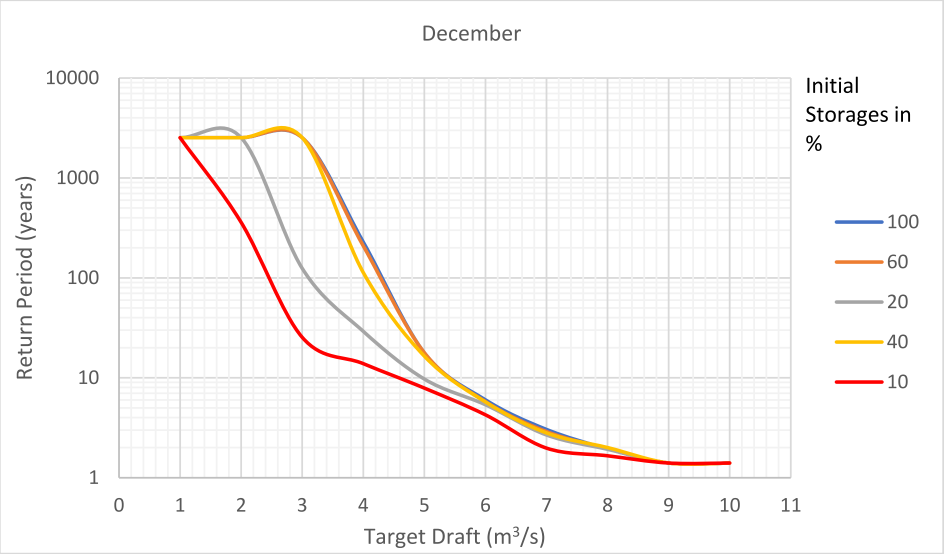


FIGURE 15 Return period–target draft curves for December.

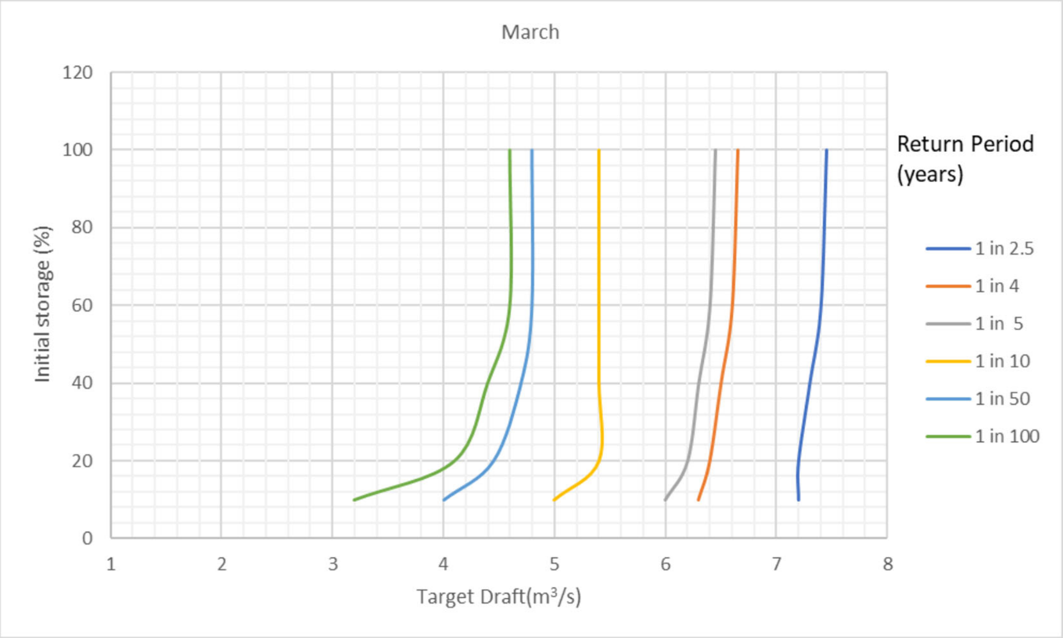


FIGURE 16 Storage states–target draft curves for different return periods for March.

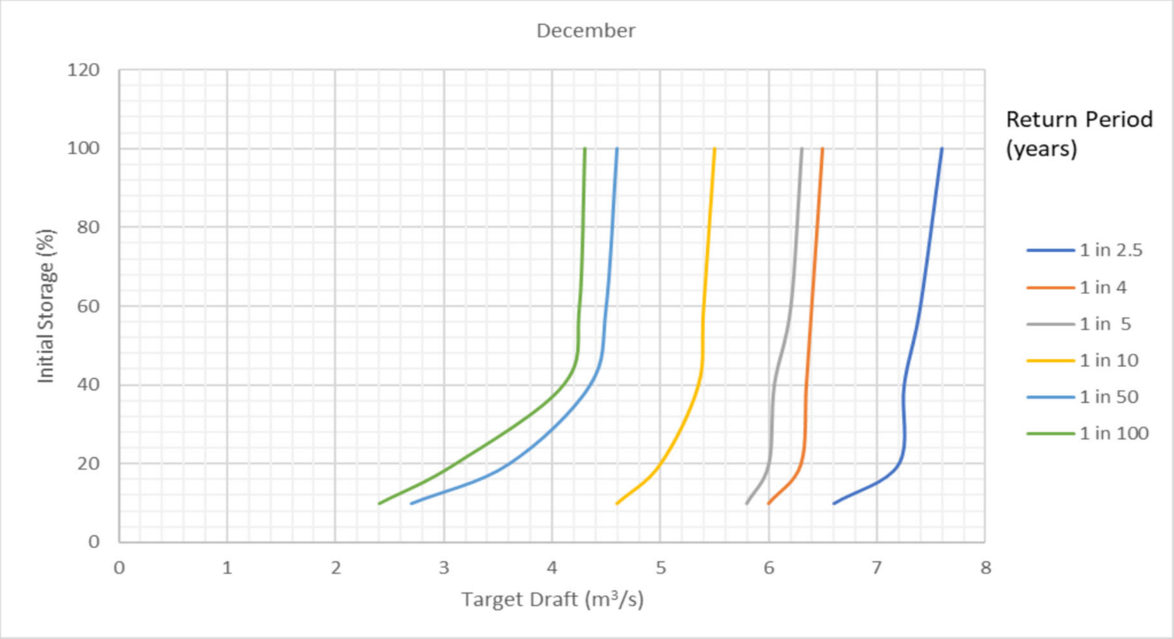


FIGURE 17 Storage states–target draft curves for different return periods for December.

TABLE 3 Supply reliability with corresponding recurrence intervals.

Reliability (%)	Corresponding return periods (years)
99	1 in 100
98	1 in 50
90	1 in 10
80	1 in 5
75	1 in 4
60	1 in 2.5

amount of water to be released will be determined based on the dam's storage state, the month of the year, and the amount of water available at Mwagu Weir.

6.3 | Application of the rule curves for operating Thika Dam

The supply levels specified in the zones between the rule curves indicate the proportion of the total demand of 6.4 m^3/s that is supplied from:

- Chania River, Kimakia River, Kiama River, and Thika Dam towards meeting the Ngethu treatment works demand.
- Thika Dam towards meeting the Kigoro treatment works demand.

The operating rule curves are therefore applied as follows:

1. The dam operator or the system managers decide on the assurance level to adopt: either the more prudent 98% or the less prudent 90% assurance.
2. The supply zone is established based on the month and storage state of the reservoir.
3. Depending on the intersection point of the initial storage state and the month of the year, the discharge to be supplied is established.
4. Based on the above, the flows to supply Ngethu and Kigoro treatment works are established using the 75%:25% ratio of the demand to Ngethu and Kigoro.
5. The flow passing through the Chania River at the Mwagu weir is measured while ensuring the ecological flow is first met and the flow available for supplying Ngethu treatment works is determined.
6. If the flow meets the Ngethu water demand, no water is drawn from the Kimakia, Kiama rivers, or Thika Dam.
7. If the Chania flow does not meet the Ngethu water demand, the water available from Kimakia, while meeting the environmental flow, is channeled towards the Ngethu demand. If the total flow meets the Ngethu demand, no flow is drawn from the Kiama River or Thika Dam.
8. If the demand is not met, the flow available at Kiama River is added, and if this still does not meet the demand, then additional water is drawn from the Thika Dam.
9. The flow determined in step 3 for Kigoro treatment works is also supplied from Thika Dam.

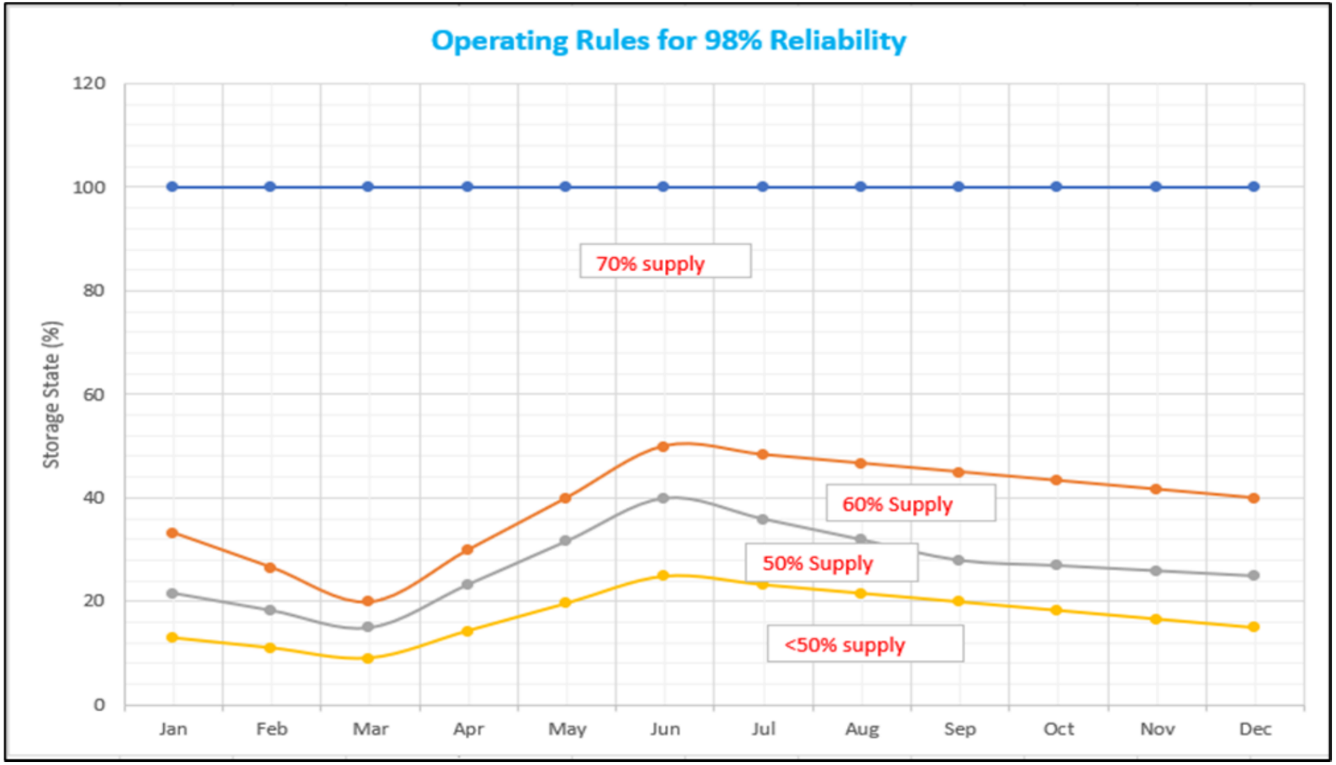


FIGURE 18 Thika Dam including NCT 1 operation curves for 98% reliability.

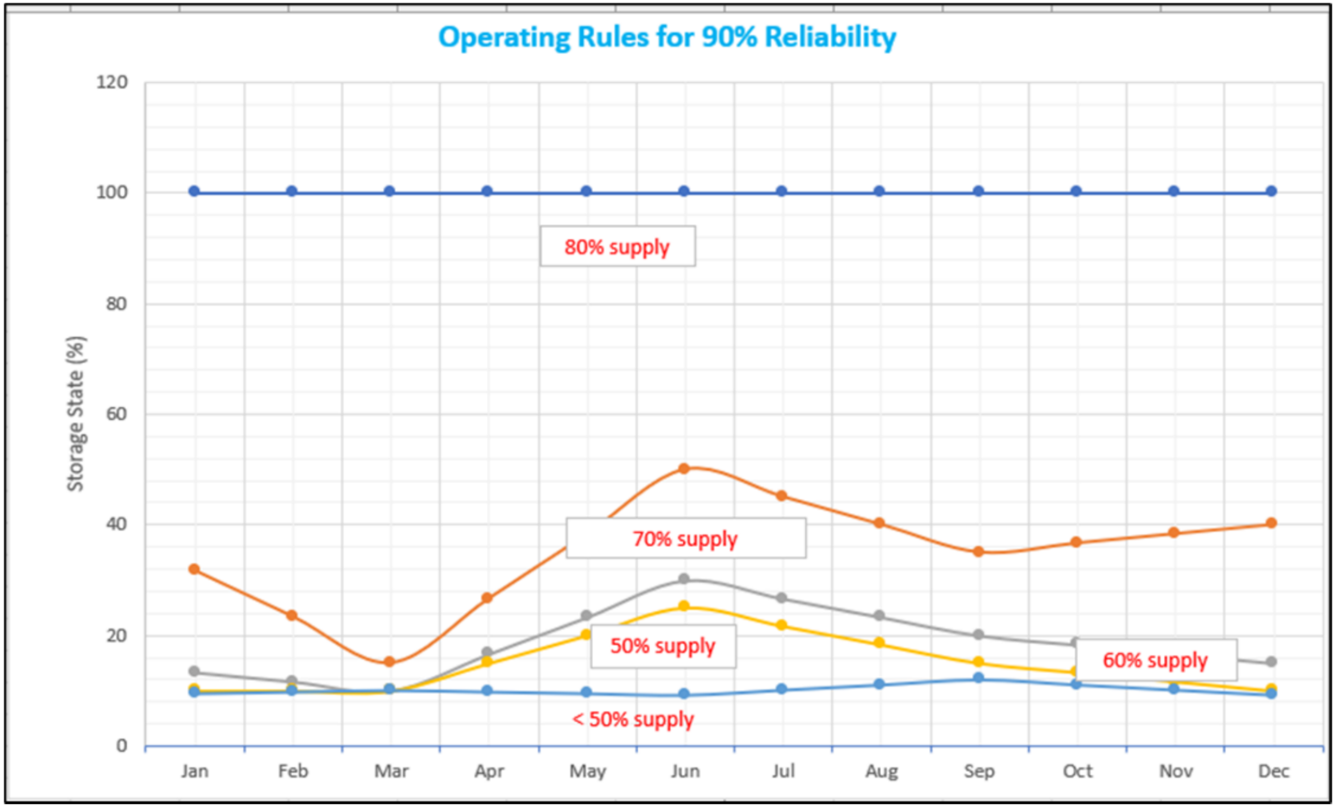


FIGURE 19 Thika Dam including NCT-1 operation curves for 90% reliability.

10. The supplies determined in steps 1 to 8 are reviewed as the Thika Dam storage state and the flows in Rivers Chania, Kimakia, and Kiama change. If need be, steps 1 to 8 are applied to determine new supplies to the two demands.

7 | CONCLUSIONS

The main objective of this study was to formulate operating rules for the Thika Dam system that do not have the limitations of the 2018 Thika Dam rules which were still in use in October 2023.

The 2018 Thika Dam operating rules were developed based on the probability of exceedance of historical stream flows from various subbasins but have three main gaps: (i) reliance entirely on historical river flows, (ii) omission of the Kayuyu River, which contributes 20% of inflows into Thika Dam, and (iii) the assumption that contributions from all rivers of specified exceedances coincided over time. A probabilistic approach that simulates the short-term system performance using multiple plausible hydrological conditions and system storage states was adopted to develop new rules that are free from the abovementioned gaps.

Historical river discharges for subbasins contributing to the Thika Dam system were modeled using the GR4J model for 1997–2022. The rivers modeled included Thika, Githika, and Kayuyu (primary inflows), Kiama, Kimakia, and Chania (Thika–Chania system), and Maragua, Gikigie, and Irati (NCT 1 system).

Using these modeled stream flows and historic rainfall and evaporation data, the VLB model was used to generate 101 stochastic streamflow, rainfall, and evaporation sequences of 1000 years each, based on 26 years of historical data. Multiple 5-year system simulations were performed to derive a large ensemble of probable system performance quantified by base yield for different initial storage states and decision months (starting month of simulation). This was done for 505 5-year stochastic sequences for each decision month and initial storage state combination. These stochastic base yields were then used to formulate reservoir rule curves for water supply at 90% and 98% reliability.

A comparison of the 2018 and the new operating rules developed herein shows the new rules are easier to understand and apply, based on the following factors: the Thika Dam storage state, the water flow rates at Chania River (Mwagu Weir), Kimakia River and Kiama River, and the month of the year. The 2018 rules require complex calculations of exceedance probabilities and the complex process illustrated in Figures 6 and 7. The modeling applied to develop the new operating rules can be easily extended to obtain operating rule curves for other reliabilities and the interpolation of the rule curves based on the analysis from four decision months could be easily replaced by an analysis using 6 or all 12 months if need be.

8 | RECOMMENDATIONS AND IMPLICATIONS TO WATER POLICY

The Thika reservoir is crucial in the water supply of Nairobi city and its surroundings. However, the water resources that contribute to the reservoir's inflows are finite, and the ecosystem that hosts these water resources has been continuously degrading from human activities and climate change, thus affecting the water supply. Therefore, it is necessary for the stakeholders, including Nairobi City Water and Sewerage Company (NCWSC) and Athi Water Works and

Development Agency (AWWDA), to ensure that the Thika reservoir operation accrues optimal benefits while maintaining high reliability. This will be achieved by using rules that consider the streamflow variabilities and incorporate all the dam inflows. The rules developed in this study have carefully considered the statistical variability of all the river flows contributing to the Thika reservoir system through stochastically generated sequences. Therefore, these rules are highly recommended for use in improving the Thika Dam operation.

The Thika Dam operating rules herein were developed using 26 years of historical streamflow, observed rainfall, and evaporation data from 1997 to 2022. We recommend creating new rules based on extensive historical datasets to ensure high statistical reliability in rule development.

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