Optimal Urban Water Allocation Strategies Under Inter-Basin Water Transfer: Case of Nairobi City, Kenya

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Abstract
Most urban cities in the world are facing water insecurity as a result of rising water demand while the supply remains uncertain due to climate variability. To curb the growing water demand, most cities in the world have invested in inter-basin water transfers (IBWTs). IBWTs have the ability to balance both the temporal and spatial distribution of water resources. To enhance their reliability, IBWTs are integrated with water storage facilities like reservoirs. The study evaluated optimal water allocation strategies with IBWT for Nairobi City. First, Sentinel imagery using normalized difference water index (NDWI), as a proof of concept, was used to investigate changes in reservoir levels of Thika dam due to IBWT.Water Evaluation and Planning System (WEAP) model was used to evaluate water allocation strategies with the new IBWT project (Northern Collector Tunnel Phase 1 (NCT 1)) and planned water sources up to year 2035. NDWI was able to detect changes in reservoir area due to the increased water flows from NCT I to Thika Reservoir. However, the increased flows from NCT I would not meet the city's water demands in the very dry, dry and normal years which had a supply coverage of 31%, 35% and 47% respectively. While the government's objective is to increase the supply coverage in Nairobi City to over 70%, this will only be achievable in the wet and very wet years as the coverage increased to 71% and 92% respectively. From the results, even with demand management measures, NCT 1 will still not meet the desired supply coverage in the very dry, dry and normal years. However, additional water sources together with demand management measures provides opportunities of alleviating water shortages by achieving the desired supply coverage under all climatic conditions. Further, the current and future water sources plans are surface water storage which are heavily affect by rainfall variability. Thus, the national and the Nairobi County governments, need to come up with an integrated water resources management system where water resources development is integrated with water demand management. Such may include supplementing centralized storage systems with decentralized ones such as rainwater harvesting, sustainable groundwater use and waste water reuses in order to enhance urban water security for Nairobi residents.

Keywords: Climatic Conditions, Inter-basin Urban Transfer, Sentinel, Water Allocation, Urban Water Security, WEAP

INTRODUCTION

More than half of the world's population live in the urban cities. Globally, urban population is expected to grow by 2.9 billion by 2050, with most of the people residing in cities of the developing countries (Nagendra et al., 2018; WWAP, 2022). There has been concerns of the increasing water scarcity in urban cities which contribute greatly towards the countries' economy. With the expansion of the urban cities, the demand for water is expected to increase while the supply remains uncertain due to climate variability. Extreme precipitation events are likely to occur more frequently and with higher intensity (Daloğlu Çetinkaya et al., 2022). Further, in some developing countries, urban growth has led to establishment of informal settlements which lack basic water and sanitation infrastructure. In the recent past, a number of urban cities have faced major water crisis for instance Cape town in 2018, San Paulo in 2015 and South East Queensland in 2007 where residents experienced unprecedented water shortages (Head, 2014; Rodina, 2019). Thus, water security in urban cities is becoming a challenge of the 21st century (Ahmadi et al., 2020; Empinotti et al., 2019; Sahin et al., 2017; WWAP, 2022). Further urban water supply has gained a lot of attention as a result of the Sustainable Development Goal (SDG) 6 which aims at achieving access of quality water to all by 2030.

In most urban cities, water scarcity solutions have been supply-driven popularized by technocrats. Governments all over the world have invested in large infrastructural projects among them inter-basin water transfers (IBWTs) in an attempt to increase water availability. Such projects are what Kumar et al., (2021) terms as critical infrastructure as they are at the core of a society's survival. IBWTs, have been used over the years to redistribute water resources to areas deemed water scarce. IBWTs are large infrastructural works often consisting of reservoirs and channels where the channels are either surface or underground (tunnels) systems. If properly planned and managed water transfers could be an effective way of improving water access in water scarce regions. However, in most of the regions, IBWTs have only temporarily solved the water scarcity problem in the recipient basin. This is because of the complex interaction of increasing water demands with variability in water supply. Thus evaluating optimal water allocation for IBWTs is vital for the schemes to achieve their objective of alleviating water shortages in the recipient basins (Zhou et al., 2017). Although there has been substantive research on the impacts of IBWT, most of the studies have been on the ecological impacts on the donor basins (Fraj et al., 2019; Quan et al., 2016; Wang et al., 2016). Little research has been done on IBWTs water allocation especially when the system relies on flood water which is highly variable. Most research on IBWTs water allocation has been on normal flow under certain climatic conditions (Sadegh et al., 2010; Sinha et al., 2020; Tian et al., 2019). The study evaluated the optimal water allocation strategies for Nairobi city with current and planned IBWTs under different climatic variability. In an innovative way, Sentinel 2 imagery was used to detect changes in Thika reservoir area resulting from introduction of NCT 1 flows. Further, the WEAP model was used to evaluate the optimal water supply options under climate variability.

Water supply development in Nairobi city

The main sources of water for Nairobi city are inter-basin water transfers from the Upper Tana River basin. The water transfer involves two main reservoirs Thika (Kiama. Kimakia and Chania rivers) and Sasumua reservoirs contributing approximately 440,000 m^3/day and 56,200 m^3/day respectively. Thus inter-basin water transfer systems account for 96% of the water supply to Nairobi city (Table 1) (AWWDA, 2016).

Population and industrial growth in Nairobi have increased water demand and competition for the water resource. According to a population census conducted in Kenya in 2019, Nairobi is the most populous city in the entire country with about 4.3 million people (KNBS, 2019). It is projected that the city's water demand will rise to approximately 1.4, 1.3 and 1.1 million m^3/day in the year 2035 under high, medium and low demand scenarios.

Table 2: Summary of the current water sources for Nairobi city (Source: AWWDA, 2016)

Source	Location	Completion year	Storage Capacity MCM	Amount in %	Amount in m^3/d	Remarks
Thika Dam	Tana river basin	1994	70	84%	414,000	Inter-basin transfer from Tana Basin
Sasumua	Tana river basin	1968	15.9	12%	56,200	Inter-basin transfer from Tana Basin
Ruiru Dam	Athi river basin	1950	2.9	4%	21,700	Intra-basin transfer (Athi)
Kikuyu Springs	Athi river basin	1913	-	0.1%	4,800	Intra-basin transfer (Athi)

The water demand scenarios were based on the high, medium and low population growth projections with a growth rate of 3.5%, 3.1% and 2.6% respectively. With the assumption that Nairobi city will follow a multi-Centric growth strategy thus regions around Nairobi will urbanize and influence the city. Further , the infrastructure development in and around the city will compound this effect. (AWWDA, 2016). Like many developing countries, investment in water supply for Nairobi has lagged since 1994 with the completion of Thika reservoir. Consequently, the current water sources are not able to meet the water demand (Figure 1). With the increasing and frequent droughts affecting river discharge, the water supply is predicated to be limited (Apse et al., 2014; AWWDA, 2016).

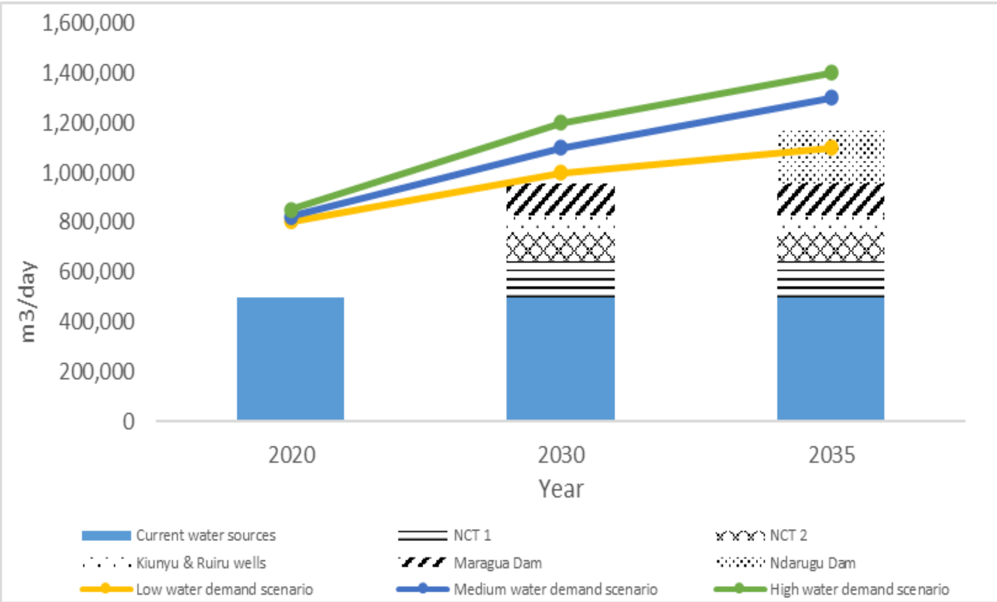

Figure 2: The water demand-supply balance for Nairobi city with the current and planned water sources (AWWDA, 2016)

To meet the growing water demand, the government has sought out new water sources relying on water transfers (Table 2). This will involve the construction of new reservoirs and expanding the Northern collector Tunnel. However, the proposed water yield from Ndarugu dam might not be feasible. This is because the towns relying on Ndarugu river for water supply have grown sporadically thus increased water demands which cannot be meet by the river. Thus, for this study Ndarugu dam as a proposed water source for Nairobi city was not considered.

Table 2: Summary of planned water sources for Nairobi city (Source: AWWDA, 2016)

Source	Expected Completion date	Amount in m^3/d	Remarks
Kiunyu and Ruiru Wells	2015	64,800	Intra-basin transfer (Not in operations)
Northern Collector Phase 1	2016	120,960	Irati, Gikigie and Maragua rivers (inter-basin transfer-completed in 2022)
Maragua Dam	2020	132,192	Inter-basin transfer (not done)
Northern Collector Phase 2	2026	120,096	South Mathioya, Hembe, Githugi & North Mathioya rivers (inter-basin transfer)
Ndarugu Dam	*2029*	*216,000*	*Ndarugu river with Chania & Komu river Inter-basin transfer*

MATERIALS AND METHODS

Sentinel data acquisition and processing

Remote sensing data is increasing gaining popularity in water resources development and management studies. Monitoring of surface water resources e.g., reservoirs has mostly been done using traditional ways of ground survey, however, the use of satellite data has shown to be valuable as it is cost effective. In the past hydrologist have shied away from using remote sensing data because of the high cost of acquisition and course resolution. However, with the advancement in technology, products like Sentinel 2 with spatial resolutions of 10m, 20m and 60 m revisiting every five days has catalyzed its use in hydrological studies (Bhaga et al., 2021).

Sentinel data acquisition

The datasets were acquired for the months of April, May and June 2022 which was based on the availability of data and because NCT 1 started operating in May 2022. The data was downloaded from Copernicus Data Access Service (https://finder.creodias.eu/). The atmospheric correction for the data set was done using the Sen2Cor processing tool in SNAP
Calculation of water index

Normalized Difference Water Index (NDWI) was selected to map changes in Thika reservoir area as a result of the contribution on NCT 1 flows. This index among many others has been used widely and successfully in mapping and detecting water bodies (Benzougagh et al., 2022; Ghansah et al., 2022; Kandekar et al., 2021; Sekertekin et al., 2018).

Validation with observed reservoir area

Estimates of Thika reservoir area from Sentinel imagery was validated with the observed reservoir area using the available elevation-area-volume graph. The observed volume and elevation sets were obtained from Nairobi Water and Sewerage Company (NWSC) who are in charge of the operations of the reservoir.

WEAP model

The Water Evaluation and Planning System (WEAP) has gained popularity over the years for modelling of water development, allocation and monitoring for proper decision making. The model enables simulation of integrated water demand, supply management strategies and supply priorities (Figure 2). It also enables the creation of scenarios to answer the 'What if' questions which are very helpful when it comes to proper planning and management of water resources (Yates et al., 2005)

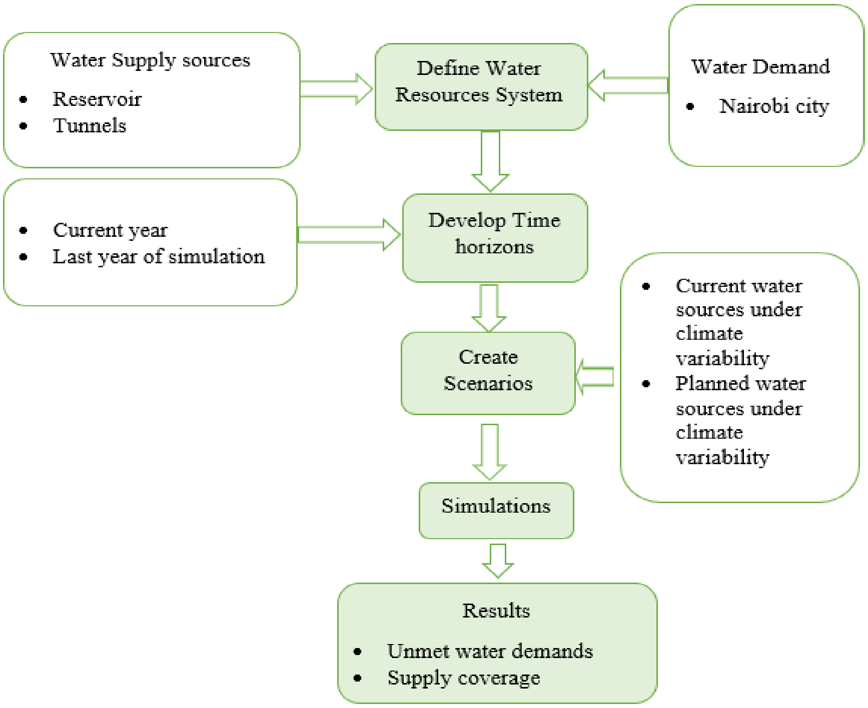

Figure 2: WEAP model framework

Data Collection

The model was developed using the data sets provided in Table 3.

Table 3. WEAP model data sets and sources

	Data Requirements	Source	Period
Water Supply	NCT 1 Rivers (Gigike, Irati and Maragua)	Hydrological modelling (Nyingi)	1997-2017
	Thika Reservoir (physical dam characterises and operating rules)	Nairobi Water and Sewerage Company (NWSC)	1997-2017
	Thika, Chania, Kimakia and Kiama Rivers	Nairobi Water and Sewerage Company (NWSC)	1997-2017
Water Demand	Nairobi City and its environs	Athi Water Works Development Agency (AWWDA)	Projected water demand 2035
	Environmental flow requirements	Athi Water Works Development Agency (AWWDA)	1997-2017

Scenarios development

B0 scenario: Water availability with the current water sources. This scenario was developed based on the current water supply as in Table 1. For the water demand, the study used the low water demands projection for the year 2022 provided by AWWDA, in 2016 of approximately 10.1m^3/s. This is because according to the 2019 census (KNBS, 2019), the population growth rate reduced from 2.9 % to 2.2 % which represented the low water demand projection.

B1 scenario: B0 + NCT 1. This scenario evaluated the effects of the new water source NCT 1. The water demand was the same as in the reference scenario.

B2 scenario*:* From literature reviewed it is predicated that effective water savings strategies are likely to reduce domestic and industrial water demand by 10-30%. This strategies may include water savings home appliances (showers, WCs, urinals and washing machines), encouraging urban rainwater harvesting and reuse of grey water (Deverill et al., 2001; Lévite et al., 2003). Based on this information and personal discussions with water managers, the study chose three options 10%, 20% and 30 % demand measures. Therefore, this scenario evaluated the impacts of a 10% demand measure on the water availability with NCT 1.

B3 scenario: B1 + 20% demand measures
In this scenario, the effects of enforcing a 20% demand measure on water availability with the implementation of NCT 1.

B4 scenario: B1 + 30% demand measures.
This scenario involved simulations of the effects of NCT 1 on water availability with a 30% demand measure.

Scenarios B5 and B6 were developed from the planned water sources: NCT Phase 2, and Maragua dam respectively.

For each of the scenarios, climate variability was included as Water Year Method provided in WEAP model. Water Year Method involved variation of stream-flow by defining five climatic conditions (very dry, dry, normal, wet and very wet). The climatic conditions were developed based on the Stream Flow Drought Index (SDI) categorization of drought in the river basin. The SDI were calculated using Drinc (Drought Index Calculator) software at a 12-month timestep (annually). The normal year was given a value of 1 whereas the other years flows are a function of the normal years (Table 4).

Table 4. Variations of streamflow for WEAP Water Year Method in Upper Tana Basin

Very dry year	0.6
Dry year	0.8
Normal year	1
Wet year	1.8
Very wet years	2.2

Model Assumptions
The initial condition of Thika reservoir was assumed to be full at the beginning of simulation. Only domestic and industrial demands were considered and the demands were taken as constant throughout the year but increased over the years as per the population growth rate. The study also assumed that the discharge series 1997-2017 represented the future discharge. Reservoir storage was assumed to be constant in that siltation effects on the reservoir were not considered.

RESULTS

Sentinel Imagery
Figure 3 shows the results of using Sentinel 2 imagery for mapping Thika reservoir area over the study period. Generally, the NDWI index was able to show changes in reservoir area once NCT 1 started operating in May 2022. The area was approximately 1.5 km^2 in

April, 1.9 km^2 in May and 2.2 km^2 in June 2022. The results were validated using elevation-area-volume curve provided by AWWDA, 2012 as shown in Table 5. In May 2022, observed flows from NCT 1 were approximately 0.14 m^3/s however by June 2022 the flows had increased to 3.52 m^3/s. The planned NCT 1 inflow to Thika reservoir is 1.4 m^3/s, from the results, in the month of May 2022, the actual flows were less than the planned. However, in June the flows increased to 3.52m^3/s.

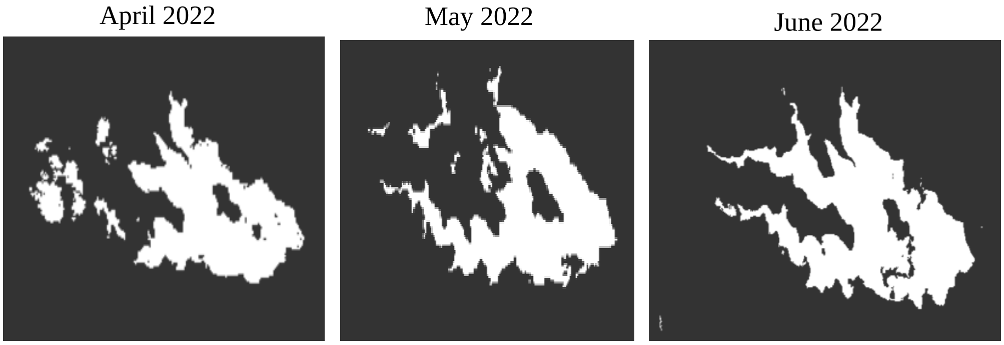

Figure 3: Thika reservoir spatial variations during the study period

Table 5: Thika Reservoir area validation with sentinel imagery

Date	Recorded (NCT 1) flow in m^3/s (source (AWWDA, 2022)	Recorded reservoir elevation (m) (source NWSC, 2022)	Reservoir vol in Mm (Source NWSC, 2022)	Corresponding area Km^2 (source (AWWDA, 2012)	Recorded rainfall in (mm) (Source NWSC, 2022)	Sentinel Area in Km^2	Agreement
08/04/2022	Operations not started	2029	41.70	1.5	0	1.58	100%
20/05/2022	0.14	2033	50.68	2.0	0	1.96	95%
30/05/2022	1.36	2034	52.62	2.1	0.2	Image not available	-
01/06/2022	3.52	2035	53.74	2.2	0	2.25	100%

The results have demonstrated as a proof of concept, the capability of Sentinel Images to detect and monitor the reservoir water balance and the future inflows from IBWT when the availability of the images is enhanced.

Water availability for Nairobi City with the current and planned water sources

Current water sources (B0) and addition of NCT 1 (B1)

The results showed that unmet demands were highest under the very dry years in both B0 and B1 scenarios. In B0 scenario, the average supply coverage was less than 30% in very dry, dry and normal years while in wet years and very wet years it increased to 41 % and 57% respectively. With the introduction of NCT 1 (B1 scenario), the mean unmet demands reduced slightly under all the climatic conditions. However, the average supply coverage in the very dry and dry years was 31% and 39% respectively.

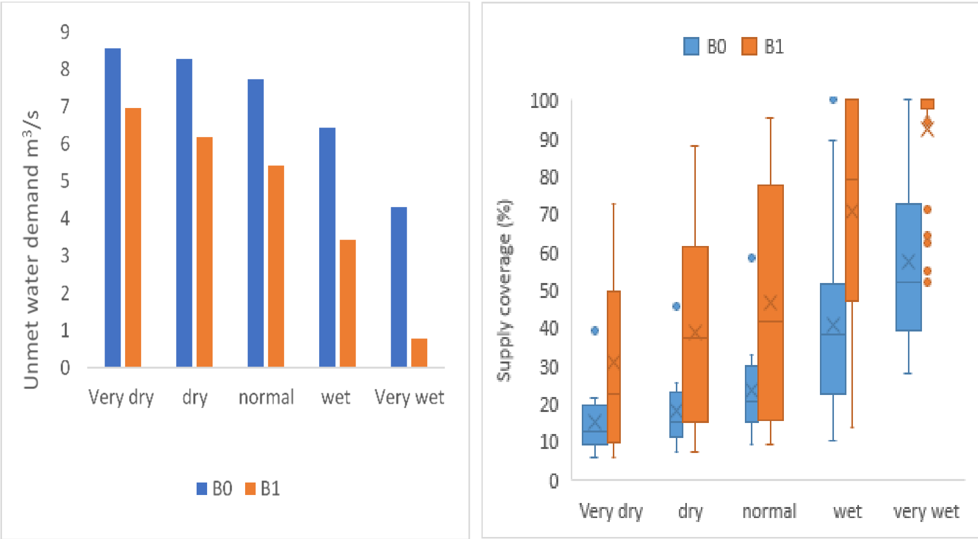

Figure 3: The unmet water demands and supply coverage under different climatic conditions in the B0 (current water sources) and B1 (B0+ NCT 1) scenarios

In the normal years the average supply coverage increased to 47% while in the wet and very wet years the coverage further increased to 71% and 92% respectively.

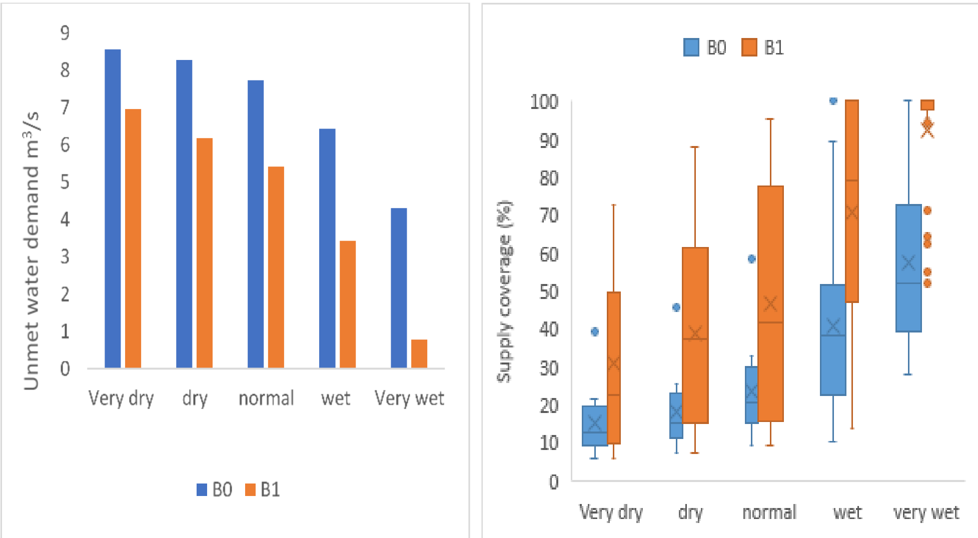

Figure 3: Unmet water demands and supply coverage in the B0 and B1 scenario

Demand measures under the B0 and B1 scenarios

With the high unmet water demands in both scenarios under the very dry, dry and normal years, simulations were done with demand measures of 10% (B2), 20% (B3) and 30% (B4) scenarios.

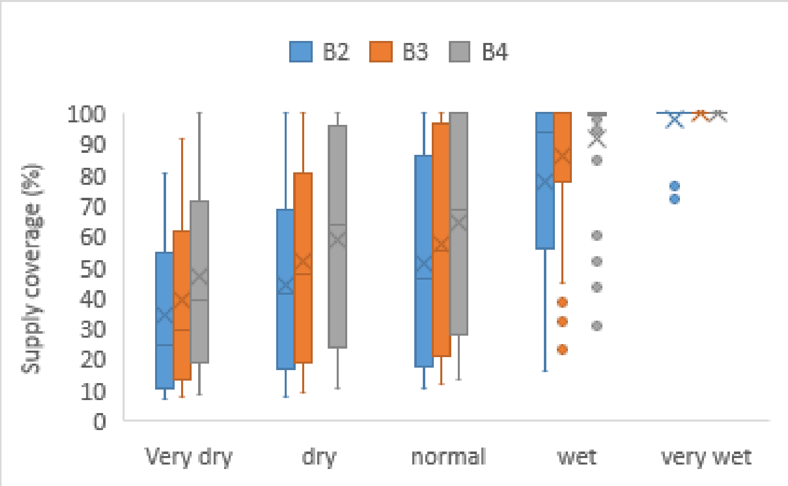

Figure 5: Water supply coverage under the B2, B3 and B4 demand measures scenarios

Results in Figure 5 showed that even with the demand measures, NCT 1 will still not meet the desired supply coverage of over 70% in the very dry, dry and normal years. More so in the very dry years the supply coverage remained below 50% under the three demand measures.

Planned water sources

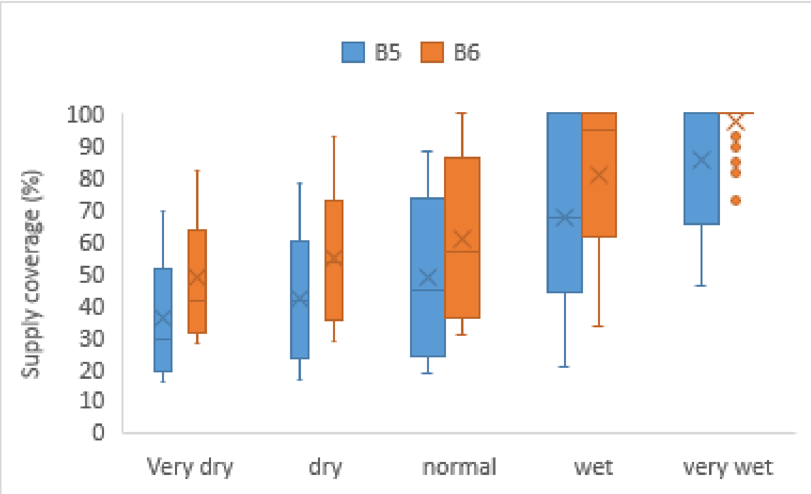

Figure 6: Water supply coverage in the B5 and B6 scenarios

Figure 6 showed that under the B5 (NCT Phase 2) and B6 (Maragua dam) scenario, the average supply coverage in the very dry, dry and normal years was still below the desired 70 %. It is only under the B6 scenario with 20% and 30% demand measures that the supply coverage in the very dry, dry and normal years rose to over 70% (Figure 7).

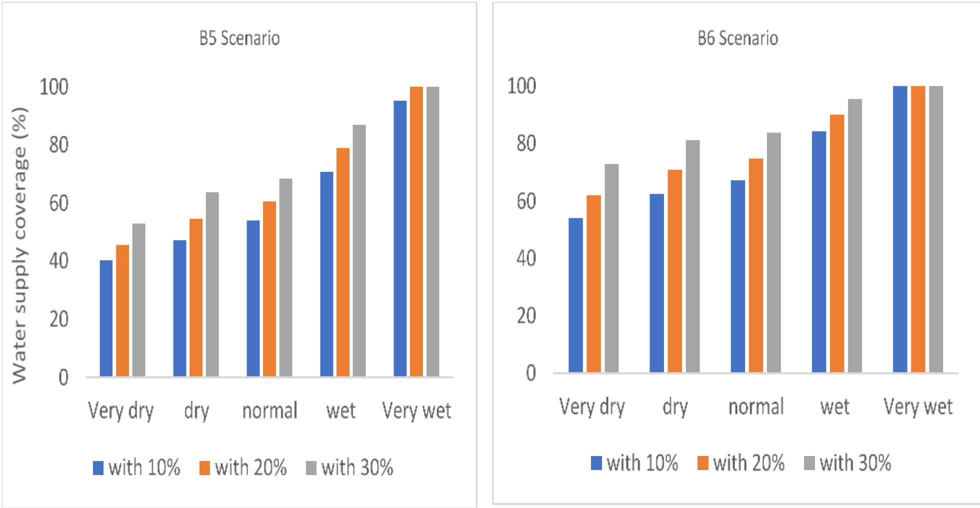

Figure 7: Supply coverage under B5 and B6 scenario with demand measures.

DISCUSSION

Satellite imagery

The results showed that it is possible to use Sentinel imagery to monitor the contribution of NCT 1 flows from changes in the reservoir area. Thika reservoir water area was highest in the month of June which had the highest recorded NCT 1 inflows. The results were in line with the water balance of the reservoir because with minimum rainfall, the month of June recorded high reservoir volume and elevation. The use of satellite data for surface water monitoring has been used successfully over the years. Bhaga et al., (2021) was able to detect and map variations in water bodies in Western Cape, South Africa during the dry and wet seasons of 2016,2017 and 2018. Their results were able to show the influence of the 2017 drought period in the region that led to severe water shortage. However, the authors noted that since the area is highly mountainous, the satellite imagery are sometimes affected by shadows. Peña-Luque et al., (2021) noted that the use of multiple dates satellite imagery improved the accuracy in detecting surface water bodies. Further, satellite imagery tends to under estimate the water area of reservoirs in areas with dense vegetation. This is because during the high filling rate periods some water may fill areas that are normally under vegetation during dry seasons making it difficult to be detected. Nevertheless, sentinel imagery provided satisfactory results in estimating reservoir levels in the Nile River basin. In addition, satellite data could be used to bridge the data gap especially in areas where the data is either scarce or unreliable (Kansara & Lakshmi, 2022).

WEAP Model

Nairobi residents relies heavily on inter-basin water to meet their growing water demand. The results showed that under very dry, dry and normal years the operations of NCT 1 will not meet the water demand and the city will have severe water shortages. Even with the most optimistic demand measures, the supply coverage under the contribution of NCT 1 remained below the government’s objective of 70% in the very dry, dry and normal years. The planned NCT Phase 2 and Maragua dam reduced the water shortages significantly under all climatic conditions, however, only with 20% and 30% demand measures did the supply coverage increase to 70% in the very dry and dry years. Although, the planned new water resources yield some hope in meeting the city’s water needs, the challenge is on timely implementation of the projects and effective water demand management strategies. Often , governments lack the financial ability to develop infrastructure in line with the growing demand (Bischoff-Mattson et al., 2020; Grasham et al., 2019; Leichenko, 2011). In addition, studies have shown that water demand increases further with the introduction of a new water source. However, research has also shown that with the use of high water efficient appliances for instance toilets, taps and showers, it is possible to reduce household water demand by 30% (Carragher et al., 2012; Lee et al., 2013; Zhuang & Sela, 2020).

Rainwater harvesting can be used as an alternative water supply system in the urban cities by meeting up to 50% of the water demand. However, it is influenced by the size of the system, climatic pattern and the water use (Steffen et al., 2013). Other non-conventional water sources like water reuse, capturing of storm water can also be solutions to urban water shortages. In addition, they will reduce the over-dependence of one source of water thus improving the resilience of the cities to climate variability (Ghosh, 2021; Nagendra et al., 2018; Sahin et al., 2017). Just like Nairobi, various cities in the world have continued to rely on surface storage for water supply to its residents. However, during periods of drought, these, water solutions have not only dried up to unprecedented levels but have caused major water crisis. In Nairobi city, most of the residents have resulted to using groundwater to meet their water needs especially during period of droughts. This has led to the increase in the number of private boreholes in the city. Consequently, the ground water levels have been reducing over time due to over-exploitation. However, studies have shown that with proper management and regulation, though limited resources, sustainable groundwater use would supplement the current water sources thus enhancing urban water security (Nyakundi et al., 2022; Oiro et al., 2020).

Thus, lessons learnt from San Paulo, Cape town, Chennai, and Australia is that there is need to combine surface water reservoir or storage with other alternative sources especially during periods of failed or lower than expected rainfall intensities (Head, 2014; Nobre et al., 2016; Rodina, 2019). There is also consensus that regulations on water conservation greatly reduce the water consumption. However, when it comes to water pricing, some authors note that the effect on water consumption is not significant while others show that although the water demand is price inelastic in a way, price strategies could influence water consumption (Hemati et al., 2016; Maggioni, 2015; Zhuang & Sela, 2020).

CONCLUSION

This study evaluated the water allocation options for Nairobi city under different climatic conditions using WEAP model. Sentinel imagery was used as a proof of concept to detect and monitor changes in the reservoir area as a result of increased inflows from the NCT 1 IBWT Project. The results showed the inflows from the IBWT varied at different times of the study period. Thus, satellite can be used to monitor variations in water availability by estimating the periodic changes in reservoir area.

WEAP analysis revealed that although, NCT 1 reduced water shortages slightly, the increased flows from NCT I would not meet the city's water demands in the very dry, dry and normal years which had a supply coverage of 31%, 35% and 47% respectively. While the government's objective is to increase the supply coverage in Nairobi City to over 70%, this will only be achievable in the wet and very wet years as the coverage increased to 71% and 92% respectively.

For the government to realize their urban water supply goal, sustainable water demand measures need to be implemented in addition to the water resource developments to meet the increasing water demand. Further, to increase the city's resilience, water managers and policy makers in Nairobi County and national governments needs to consider alternative water sources other than surface water storage through IBWTs. Such may include decentralized water supply options like rainwater harvesting and waste water reuse. In addition, with proper management and regulation groundwater could be an alternative water source to enhance urban water security.

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