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RESEARCH ARTICLE

Modelling the water supply-demand relationship under climate change in the Buffalo River catchment, South Africa

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Abstract

Climate change strains the global water supplies' capability to meet demands, especially in regions like South Africa, where resources are already scarce. The interconnectedness of water, energy, and food (WEF) exacerbates this challenge, amplifying the impact of climate change on water resource management across these sectors. Thus, in strengthening the long-term resilience and reliability of water resources, a necessity in South Africa, research on climate change and the WEF nexus is needed for water resource planning and development. Employing the WEF nexus approach, we applied the Climate Land-Use Energy and Water Strategies (CLEWS) modelling framework to assess climate change impacts on the water supply-demand relationship, considering the domestic, agriculture (irrigation) and energy generation sectors, and adopting the Buffalo River catchment, KwaZulu-Natal, South Africa, as a case study. A threefold approach was utilized: (1) water supplies and demands and the total unmet demands were quantified; (2) the percentages of water demands covered per sector were derived; and (3) the reliability of the water system to meet each sector's water demands was computed. The findings projected slight decreases (2%) in the Buffalo River catchment's total water demands towards the end of the 21st century, mainly due to changes in land suitability for agriculture. While the water system is projected to be reliable for highly populated municipalities (demand coverage index > 70%; reliability index $\geq$ 20%), it is unreliable for sparsely populated and agriculturally intensive municipalities (demand coverage index $\leq$ 12%; reliability index = 0%). Such unreliability will strain agricultural production as more than 70% of irrigation water demands come from these municipalities. Nexus-smart water allocation and capacity development plans are recommended to manage these challenges and ensure a just and sustainable water supply-demand relationship in light of climate change.

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Introduction

Human activities such as agricultural production, energy generation, population growth, and socio-economic development are increasing global water demands and competition for water supplies. This presents significant risks to the reliability of water supplies to satisfy demands in light of climate change [1, 2]. Thus, to reduce conflicts and optimize water supply and demand management, it is vital to evaluate the key factors that drive conflict in the water supply-demand relationship and consider how they could change and affect each other under climate change [3–5].

With the intent of identifying key factors influencing water resource management globally, a "nexus" among food, energy, and water was established at the 2008 World Economic Forum [6, 7]. The Water-Energy-Food (WEF) nexus refers to the interconnections among water, energy and food systems [8]. Extensive research and applications of the WEF nexus approach to resource management have been conducted worldwide [2, 9]. However, studies focusing on applying WEF nexus planning in Africa have been limited, which contributes to the approach's delayed adoption [10]. In South Africa, numerous studies have identified the primary obstacles to cross-sectoral coordination in resource management being the widespread lack of understanding and practical cases demonstrating the implementation of the WEF nexus approach [11–14]. This underscores the pressing need for South Africa to adopt nexus thinking in policy formulation and planning, given the country's ongoing struggles with water scarcity, increasing energy and food demands, and inadequate systems for climate change adaptation [15, 16]

The Climate, Land-use, Energy, and Water Strategies (CLEWS) framework, initially proposed by the International Atomic Energy Agency, is a WEF nexus approach that integrates the climate system in the exploration and analysis of the linkages between WEF resource systems [17]. The CLEWS framework generally addresses multiple objectives, the most widespread being cross-sectoral policy assessments combined with sustainable resource management [18]. The framework has gained traction in academic, national, regional, and local policy development spheres [12, 18, 19].

Ramos *et al.* [18] reviewed the CLEWS framework's phases and applications, highlighting key research contributions, including studies in Africa, such as (a) the 2012 CLEWS study in Mauritius assessing biofuel policy coherence [20], (b) the 2018 CLEWS investigation in Ethiopia on energy policies amid climate change and (c) the 2015 CLEWS analysis in Cape Town on energy implications of water supply expansion and land use changes [19]. Stakeholder involvement is also heavily emphasized when undertaking a CLEWS assessment to ensure scenario development aligns with development plans [21].

Most of the CLEWS assessments are devoted to assessing and developing policy recommendations from an energy viewpoint, primarily bioenergy use and electricity grid pathways, as this was the main focus of the framework's initial development, and the basis of the CLEWS single-use Open Source Energy Modelling System (OSeMOSYS) tool [18]. While global water and energy assessment are gradually increasing, there is still a lack of land and climate change assessment utilizing the CLEWS framework [18, 22]. This is reflected in South African CLEWS studies, which employ the framework from a water and energy perspective [19, 23, 24].

With over 98% of South Africa's surface water already allocated (21), the strain on water resources is expected to worsen due to projected climate change impacts [25]. Given such, we conducted a CLEWS assessment from a South African catchment perspective, to quantify the impact of climate change on the water supply-demand relationship, considering the potential changes in land suitability for agriculture, population growth, and energy production. Using the Buffalo River catchment in the KwaZulu-Natal province, South Africa, as a case study, this study presents a prospective assessment of the catchment's water supply system's capacity and reliability to meet demand, to aid in strategic thinking towards integrated water resource planning and management.

The Buffalo River catchment has not been able to fulfil increasing water demands in recent years even though it is a high rainfall region receiving, on average, 802 mm/annum [26]. This water supply deficit is also expected to continue under climate change, irrespective of the anticipated rises in average rainfall and surface water availability. Dlamini *et al.* [27] projected increased unmet demands in the Buffalo River catchment due to climate change-induced increases in rainfall variability, yielding low temporal water storage. We find this in many regions across the world, such as the Yellow River catchment in China [28], central-eastern Mexico [29], South Asia [30], and in the south of Marrakech, Morocco [31], whereby inadequate water supply facilities and management, as well as climate change impacts, threaten to strain the water supply-demand relationship, despite the region having ample water resources to supply the population.

As it stands, the Buffalo River catchment's water supplies have been characterised as unreliable by the local municipal authorities, which depend upon it for water, thus requiring remodelling [26, 32, 33]. Building on the Dlamini *et al.* [27] study, which projected demands from energy and irrigation to follow historical trends, the current study aims to improve this by further investigating: (a) the potential consequences of climate change on the catchment's primary water users and (b) the reliability of water infrastructure and allocation plans to meet projected water demands. This study was based on the null hypothesis that climate change does not influence the correlation between water supply and demand. The findings offer valuable insights into the water supply-demand dynamics' sensitivity to climate change, and key areas of intervention for addressing current and future water resource management challenges.

Materials and methods

Description of case study–Buffalo River catchment

The Buffalo River catchment forms part of the uThukela Water Management Area in northern KwaZulu-Natal, South Africa. The study area, shown in Fig 1, has maximum coordinates of 28˚42'59" South latitude and 30˚38'30" East longitude [26]. The total area of the catchment is 9 803 km^{2,} and it covers parts of the Amajuba and uMzinyathi District Municipalities. The study area primarily provides water for irrigation, energy generation, mining, and bulk industries. The climate of the Buffalo River catchment can be described, in the South African context, as a high rainfall area, receiving on average 802 mm of rainfall per annum. Due to the intense precipitation variability, the catchment has faced drought conditions in the past years, especially during 2015 and 2016, which threatened the ability of water supplies to meet demands [26]. Therefore, the implications of possible climate change outcomes on the Buffalo River catchment's capability to meet its water demands must be evaluated.

CLEWS modelling framework and tools

The modelling framework and tools used to carry out the integrated reliability assessment of the Buffalo River catchment's water system were chosen among the available Water-Energy-Food (WEF) nexus frameworks and tools. The WEF nexus is a methodology that '*considers the interlinkages*, *synergies*, *harmonisation and trade-offs when managing water*, *energy and food resources* [34]. As this study aims to investigate the implications of climate change on water systems and reliant energy and agriculture activities, the WEF nexus is ideal given that it provides a wide range of analytical tools and frameworks for understanding how WEF resources interact with one another under pressures such as climate change [35].

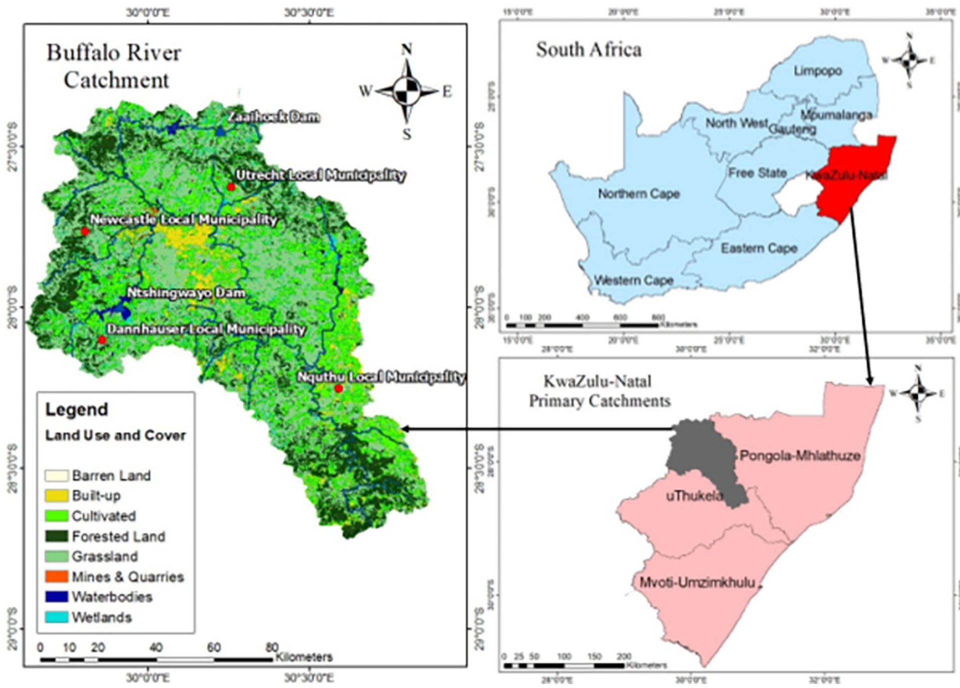

Fig 1. Schematic of the Buffalo River catchment with local municipalities (red circle nodes) and the main reservoirs (blue triangle nodes). The vector shapefiles were retrieved from the South African Department of Water and Sanitation (https://www.dws.gov.za/iwqs/gis_data) and Standford University's online library (https://earthworks.stanford.edu). The map was created using ESRI's ArcGIS Software Version 10.6.0.8321.

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Analytical approaches suitable for use in South Africa that deal specifically with WEF resources management and climate change are the Climate, Land-Use, Energy and Water Strategies (CLEWS) approach and the ANEMI model. While the ANEMI model carries out an interconnected evaluation of the physical, ecological, and hydrological processes [12, 36], the CLEWS approach can be carried out using a single model, or by soft-linking and hard-linking (mixed methods approach) different land, energy and water models under various climate scenarios. Therefore, the CLEWS mixed methods approach was selected based on its flexibility of analytical model selection for each WEF component [12].

The Long-range Energy Alternatives Planning (LEAP) model is a typical CLEWS analytical tool for energy system analysis. LEAP is an integrated, scenario-based modelling tool [37], well-fitting to this study's intended aim of analysing the water system's reliability under different climate change scenarios. LEAP also allows tracking energy consumption, production, and resource extraction in all sectors of the economy [37]. The Water Evaluation and Planning (WEAP) model is generally used for water system planning in CLEWS [38]. WEAP's advantage is that it is a scalable resource planning tool that compares water supplies and demands and provides capabilities for forecasting demands [39]. The modelling of the land-use system was not set up as an integral part of this assessment. Instead, results from a global assessment made by the Food and Agricultural Organisation (FAO) and the International Institute of Applied Systems Analysis (IIASA), known as the global Agroecological Zones (gAEZ) assessment, were used [40]. Fig 2 displays the interactions between models and data flow using the CLEWS approach, forming the basis of this study's methodology.

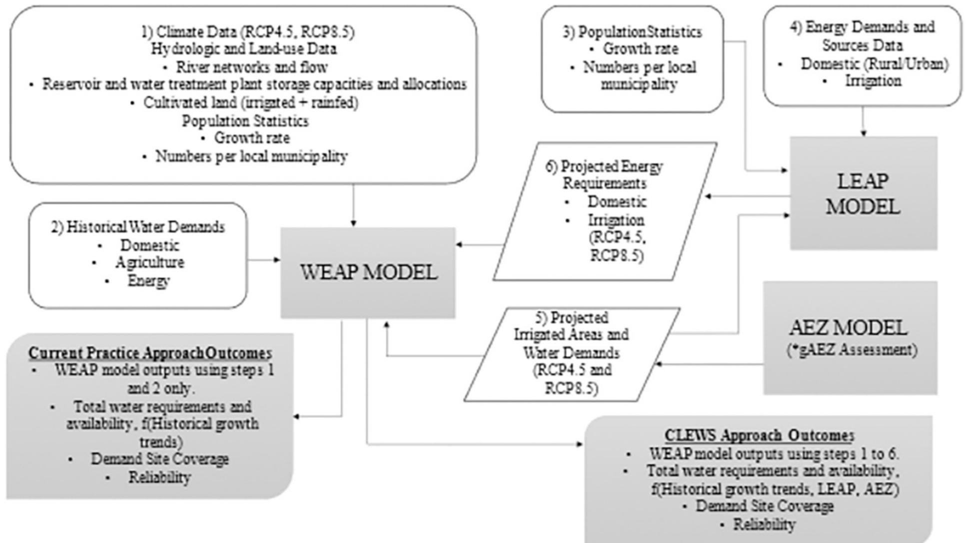

Fig 2. Diagram showing the data flow and expected results using the CLEWS approach adapted from [20].

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Current practice approach

The Current Practice Approach (CPA), also shown in Fig 2, was established as the initial step of the CLEWS modelling approach. The CPA was detailed and performed by Dlamini *et al.* [27]. In the CPA, the WEAP model was solely used to simulate and project the effects of rainfall variability on streamflow and net surface water storage without explicitly considering the effects of changes in land use and energy systems over time. In investigating climate change impacts on surface water availability, precipitation output data from global circulation models (GCMs) based on the Representative Concentration Pathways (RCP) 4.5 and 8.5 climate change scenarios was utilised as input data to the WEAP model. The projected net surface water supply changes, i.e., surface water available after water abstractions, were compared to the historical simulated values. According to the assessments, climate change is expected to increase precipitation, leading to increased evapotranspiration and surface runoff. As the frequency of peak flooding events increases, climate change is expected to increase surface water availability through recharges of surface water storage [27]. Tables 1 and 2 summarise the CPA's key data inputs and study findings, extracted from and explained in Dlamini *et al.* [27].

CLEWS approach

The RCP4.5 and RCP8.5 climate change scenarios assessed in the CPA were reassessed using the CLEWS approach, also shown in Fig 2, to further investigate the relationship between water demands and the availability and reliability of water supply under climate change considering the following additional linkages from the water, energy and agricultural systems:

a. Irrigation water requirements (IWR) are used to produce the projected agroecologically attainable yield of the catchment's irrigated commercial crops (derived from the gAEZ land-use assessment).

b. Energy demands for irrigation and household (derived using the LEAP model).

c. Water demands for producing LEAP energy demands (derived from the WEAP model).

Table 1. Summary of Water Evaluation and Planning (WEAP) model input parameters [27].

Data type	Source	Timeline	Description
GIS-based vector data	Department of Water and Sanitation	-	Vector maps of: (a) KwaZulu-Natal's (KZN) secondary drainage regions, (b) KZN district municipalities, (c) river networks of Amajuba and uMzinyathi district municipalities.
Historical precipitation data	Climate Hazards Group InfraRed Precipitation with Station dataset	01/01/1990–31/12/2019	0.05° pixels of gridded precipitation data
Precipitation projections	NASA Earth Exchange Global Daily Downscaled Climate Projections dataset	01/01/2020–31/12/2099	Statistically downscaled climate data for RCP4.5 and RCP 8.5, extracted from climate models ACCESS1-0, MIROC-ESM-CHEM, CCSM4, CNRM-CM5, MPI-ESM-L, NorESM1-M
Reference Evapotranspiration	MODIS 16 Global Terrestrial Evapotranspiration Product (MOD16)	01/01/2001–31/12/2014	8-day reference evapotranspiration data
Population statistics	Statistics South Africa (StatsSA)	2005–2016	Population data including: (a) capacity, (b) growth rate, (c) water consumption
Land use data	Statistics South Africa (StatsSA), Department of Agriculture, Land Reform and Rural Development (DALRRD)		Data including: (a) irrigated land area, (b) irrigated crop types and (c) irrigated water requirements
Surface water supply	Umgeni Water Infrastructure Master Plan 2020: Buffalo System	-	Data on surface water infrastructure including: (a) storage capacity, (b) reservoir elevation, (c) net evapotranspiration, (d) extraction quantity and (e) surface area of reservoirs.

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Land-use modelling. Fig 3 summarizes the methodology used to retrieve the attainable yields and their respective irrigation water requirements for irrigated commercial farmlands in the Buffalo River catchment using the global Agro-Ecological Zones (gAEZ) assessment. The gAEZ land-use assessment relies on well-established land evaluation principles to assess natural resources for finding suitable agricultural land utilization options [40]. The results of gAEZ's crop suitability and land productivity evaluation are stored as separate databases, each organized in terms of 5 arc-minute (about 9 x 9 km at the equator) grid cells accessed at https://gaez.fao.org [19].

Land classification, suitability mapping and crop summary tables. The gAEZ assessment aimed to extract information on the catchment's projected attainable agricultural yields and irrigation water requirements under climate change. In the Buffalo River catchment, maize, wheat, oats, soybean, and ryegrass are the most dominant irrigated crops. Therefore, the study employed these crops in the analysis of irrigated agriculture. Sprinkler-irrigated commercial farmlands were chosen due to a lack of data in the assessment regarding forecasts of irrigated subsistence farmlands and other types of irrigation systems.

Historical and projected crop suitability classification maps were extracted and analysed using the ArcGIS software. It is important to note that the gAEZ assessment's historical

Table 2. Summary of current practice approach results [27].

Variables	Timeframe						
	Historical	Near future		Mid-future		Far future	
		RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5
Precipitation (mm/annum)	7 859 (+7.9%)	7 864 (+7.9%)	7 707 (+8.1%)	7 884 (+6.5%)	8 207 (+8.5%)	8 125 (+6.7%)	8 286 (+8.5%)
Evapotranspiration (Mm^3/annum)	-4 863 (10%)	-4 516 (+7.5%)	-4 379 (+8.6%)	-4 532 (+7.9%)	-4 738 (+8.1%)	-4 548 (+9%)	-4 458 (+8.4)
Streamflow (Mm^3/annum)	-3 028 (19%)	-3 034 (+17%)	-3024 (+17%)	-3 046 (+22%)	-3 467 (+22%)	-3 267 (+18%)	-3512 (+18)
Water Abstractions (Mm^3/annum)	-114	-115	-114	-114	-114	-115	-114
Net Surface Water Store (Mm^3/annum)	-237	-276	-261	-277	-278	-287	-280

Percentage values in brackets indicate the coefficient of variation[*]

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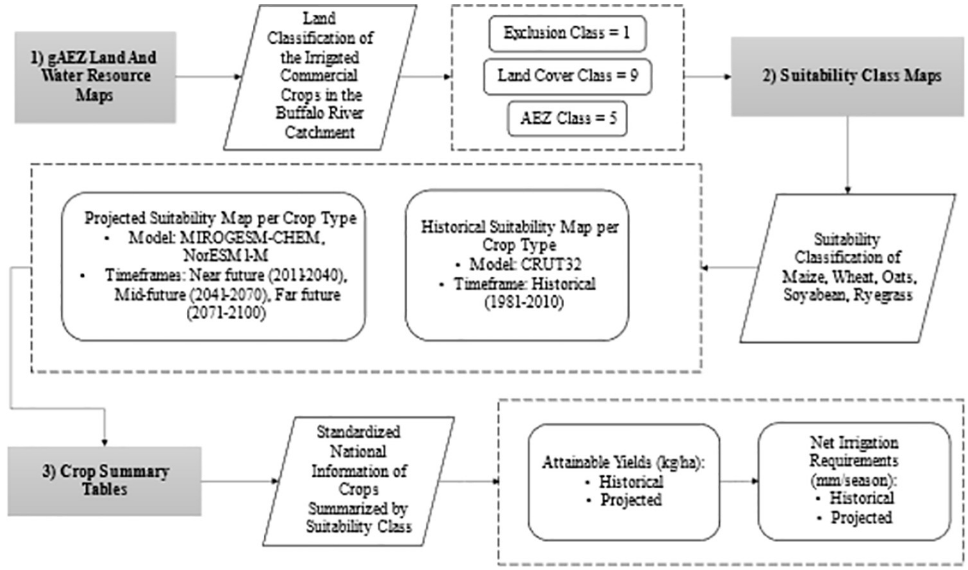

Fig 3. Global agro-ecological zones (gAEZ) assessment's data extraction flow chart.

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suitability maps were created based on the CRUT32 model output data from 1981 to 2010, and projected suitability maps used numerous GCMs detailed in Fischer *et al.* [40]. To maintain consistency in projections, suitability maps produced using MIROC-ESM-CHEM and Nor-ESM1-M climate models were considered based on these GCMs outputs included in the precipitation projection analysis (see Table 1). After assigning each local municipality in the Buffalo River catchment with a suitability class per crop type described using Table 3, crop summary tables were used to determine the agro-ecological attainable yield per crop type, alongside the net irrigation requirements, to obtain the yield.

Bias correction. The agricultural production and land statistics presented in crop summary tables are at a national scale. Hence, Fischer *et al.* [40] suggested downscaling outputs when aggregating national production statistics to individual spatial units. Therefore, the projected attainable yields were bias-corrected using the linear scaling (LS) equation presented in Eq (1), as it maintains the observed parameter's average [41]. The bias correction process used records of irrigated commercial crop production yields in the Buffalo River catchment, obtained from StatsSA [42] (see S1 Fig–S3 Fig in the Annexure). The same bias correction methodology was applied to the irrigation water requirement projections.

Table 3. Global agro-ecological zone (gAEZ) assessment's suitability class description [40].

Acronym	Suitability Description	Farm Economics
VS	Very suitable land (80–100% of maximum attainable yield)	Prime land offering the best conditions for economic crop production
S	Suitable land (60–80%)	Good land for economic crop production
MS	Moderately suitable land (40–60%)	Moderate land with substantial climate and/or soil/terrain constraints requiring high product prices for profitability
mS	Marginally suitable land (20–40%)	Commercial production is not viable. Land could be used for subsistence production when no other land is available
vmS	Very marginally suitable (<20%)	Economic production not feasible
NS	Not suitable	Production not possible

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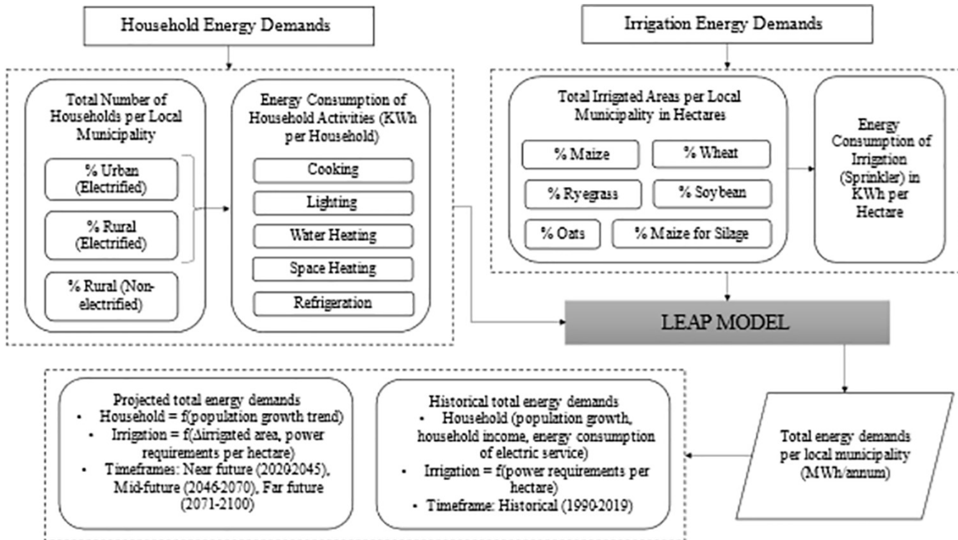

Fig 4. Long-range Energy Alternatives Planning (LEAP) model flow chart for modelling household and irrigation energy demands.

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$$CY_{corr} = CY_{raw} \times CF \tag{1}$$

where CY_{corr} = bias corrected crop yield (kg/ha)

CY_{raw} = raw crop yield data (kg/ha)

CF = correction factor = $^{CY_{observed\ data}}/_{CY_{raw\ data}}$

Energy modelling. The modelling of the energy demands was achieved using the Long-range Energy Alternatives Planning (LEAP) model, version 2020.1.0.69, developed by the Stockholm Environment Institute (SEI) [43, 44]. The analysis covers irrigation and household energy demands, as seen in Fig 4, in each local municipality within the Buffalo River catchment.

Changes in irrigated areas. The water use efficiency parameter (WUE), defined as the ratio of crop yield to applied water [45], was utilised to compute the projected changes in irrigated field sizes (ha) using Eqs (2) and (3) [46]. Each crop type's historical WUE was computed using irrigated crop yield data from StatsSA [42] and irrigation water requirements from Stevens *et al*. [47] and DAFF [48] (see S1 Table in the Annexure) and kept constant throughout the study period. Employing the gAEZ's projected attainable yield and irrigation water requirements, the projected irrigated areas were calculated using Eq (3) [46, 49].

$$WUE = {}^{C}Y/_{(}IWR \times A) \tag{2}$$

where WUE = Water use efficiency (kg/ha.mm)

CY = Crop yield (kg/ha), and

IWR = Irrigation water requirements (mm/ha)

A = Irrigated area (ha)

$$A_{new} = \frac{CY_{new}}{WUE} \times IWR_{new} \tag{3}$$

where A_{new} = Projected irrigated area (ha),

CY_{new} = Projected crop yield (kg/ha),

IWR_{new} = Projected irrigation water requirements (mm/ha/(season))

Computing power requirements for irrigation. As per the gAEZ assessment, only sprinkler irrigation was considered for irrigation energy consumption. The power requirements per crop type per hectare (P) were calculated using Eq (4) [49, 50].

$$P = \frac{C_e}{En_c} \tag{4}$$

where P = power requirements for water application (kWh/ha/year),

C_e = annual energy cost to operate centre pivots (R/ha/year),

En_c = energy rates (R/kWh).

In computing the historical energy rates (En_c) values shown in Fig 5, the average Eskom rates for rural/farming users in Rands per kilowatt-hour (R/kWh) were obtained from Eskom's annual reports (ESKOM [51]). According to Venter *et al.* [52], approximately 80% of registered irrigation systems in South Africa are pressurized types, which include centre pivots, sprinklers, drip and micro-sprinkler systems, and commercial farmers tend to be more favourable towards centre pivots [53]. As irrigated commercial farmlands are considered in this study, it was assumed that all irrigation in the catchment is conducted using centre pivots.

For the annual energy cost to operate centre pivots (C_e), the values are the sum of fixed and variable electricity costs [49, 50]. Fixed electricity costs are constant and can only be changed by the electricity supplier, Eskom [52]. The variable electricity costs are due to irrigation hours, kilowatt (kW) requirements and the electricity tariff. A study conducted by Venter *et al.* [52], compared the total electricity costs of operating a small (30.1 ha) and large (47.7 ha) centre pivot under the 2018 Landrate and Ruraflex electricity tariffs at different system delivery capacities (see Table 4), and found that Ruraflex is more profitable than Landrate irrespective

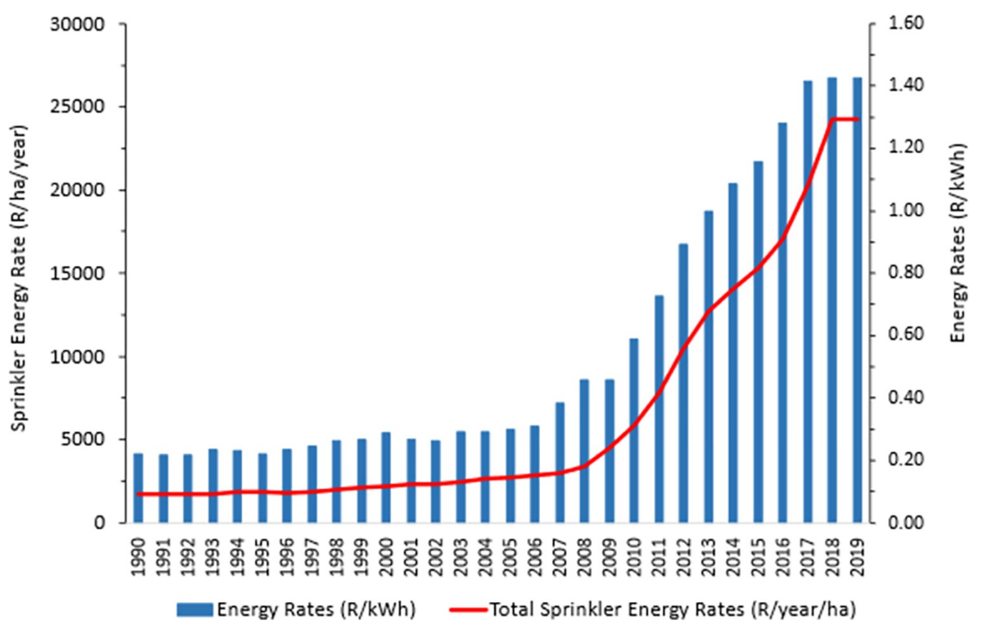

Fig 5. Eskom's energy rates (R/kWh) for rural and farming activities [51] and total sprinkler energy rates (R/year/ha) derived using the Ruraflex electricity tariff.

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Table 4. Optimal investment and electricity costs for operating a small and large centre pivot using Eskom's Ruraflex electricity tariff [52].

Centre Pivot Size (ha)	Small (30.1)				Large (47.7)			
Irrigation System Delivery Capacity (mm/day)	8	10	12	14	8	10	12	14
Total Variable Electricity Costs (R)	541 411	549 204	508 959	494 362	849 125	865 063	832 717	883 347
Total Fixed Electricity Costs (R)	307 099	307 099	307 099	307 099	307 099	307 099	394 056	394 056
Total Electricity Costs (R)	848 510	856 303	816 058	801 461	1 156 224	1 172 162	1 226 773	1 277 403
Total Electricity Costs (R/ha)	28 190	28 449	27 112	26 627	24 240	24 574	25 719	26 780

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of the centre pivot size and irrigation system delivery capacities. Thus, the Ruraflex electricity tariffs were used in this study.

As Eskom introduced the Ruraflex electricity tariff in 2003, its tariff growth rates since then have been utilized to interpolate the variable electricity costs based on the 2018 value in Table 4. C_e value of the large centre pivot with a system delivery capacity of 8 mm/day was deployed in this study since it was the most profitable system. The Ruraflex tariffs were obtained from ESKOM [51]. From 1990 to 2003, due to insufficient available records, it was assumed that the variable electricity costs' growth rates were the En_c rates. Fig 5 displays the growth trends of C_e under the historical period; these trends were duplicated throughout the study period.

Household electricity consumption. Before computing household electricity consumption, data related to the number of households and settlement types in each local municipality in the Buffalo River catchment was gathered, as seen in Table 5. Due to South Africa having higher electrification rates in urban households than rural households [54], and the Amajuba district municipality, which covers the Newcastle, Dannhauser and Utrecht local municipalities, having its bulk electricity infrastructure concentrated in urban areas [55], urban households were assumed to be fully electrified. The rural households were divided into electrified and non-electrified; for the study, the non-electrified rural households were not considered. For electrified households, data from StatsSA [56] on the percentage of households having access to the following energy services was also collected, which is only available for 2015: cooking, lighting, water heating, space heating, and refrigeration (see S4 Fig to S8 Fig in the Annexure).

The Buffalo River catchment's local municipalities' households were classified, employing the incomes in Fig 6, into income groups using the following categories: low-income households make less than R86 000 per year (pa), middle-income households make between R86 001 pa and R1 480 000 pa, and high-income households make more than R1 480 001 pa (30). From the classification, the Buffalo River catchment's local municipalities were found to be

Table 5. Household statistics of local municipalities within the Buffalo River catchment.

Local Municipality	Household Numbers			Household Size		Settlement Distribution	
	2001	2011	2016	2011	2016	Urban (%)	Rural (Electrified) (%)
Newcastle	71 164	84 271	90 347	4.3	4.3	40, 45', 39"	11
Utrecht	6 184	6 252	6 667	5.5	5.5	10	55
Dannhauser	19 320	20 580	20 242	5	5.2	10.1	26
Nquthu	29 417	31 610	32 622	5.2	5.3	10.7	66
Source(s)	[57, 58]	[56]				[59–63]	

For the Newcastle Local Municipality's urban settlement distribution: 1996 = 40%, 2001 = 45%, 2007 = 39%. The rest of the urban settlement distribution statistics are reported for 2011.

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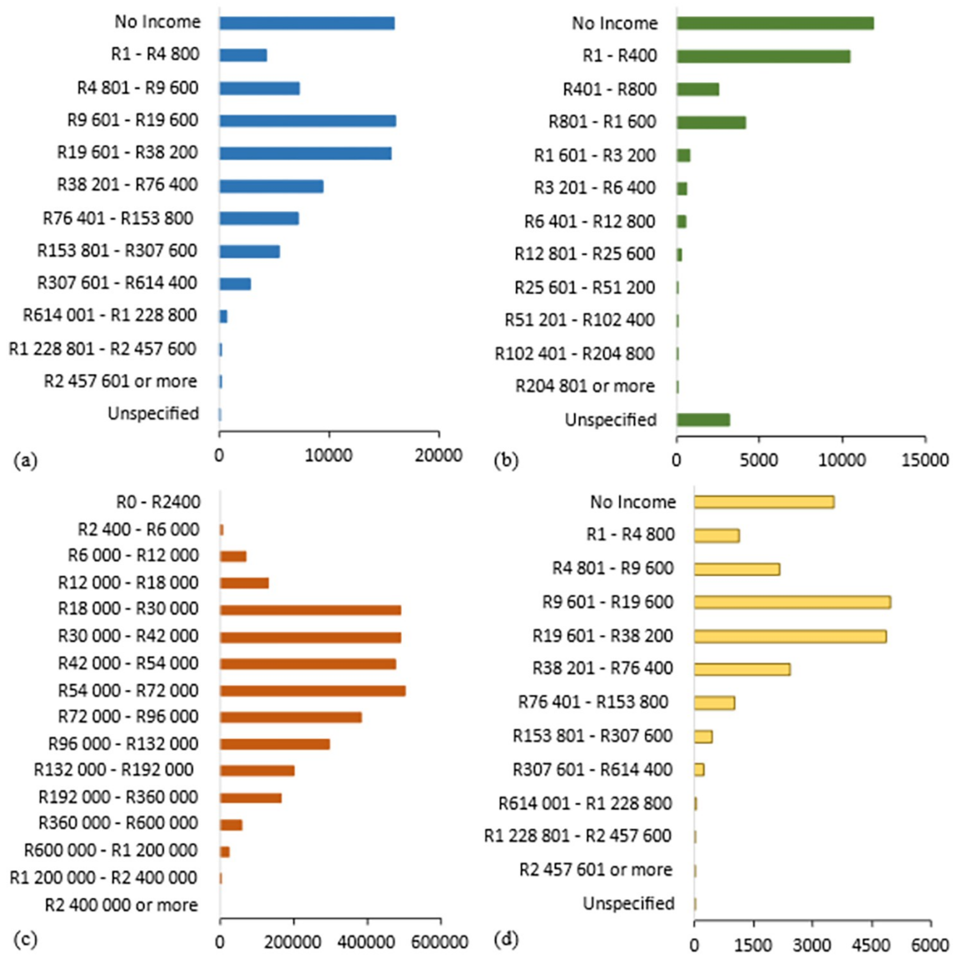

Fig 6. Household incomes per annum of the (a) Newcastle local municipality [59], (b) Utrecht local municipality [60], (c) Nquthu local municipality [62] and (d) Dannhauser local municipality [61].

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predominantly low-income households. Using the South African energy intensity/consumption of electric appliances per household quantified in a recent study by Dinkwanyane *et al.* [64] for low-income groups (S2 Table in the Annexure), the household electricity consumption was modelled using the LEAP model. Eq (5) briefly describes the LEAP modelling process using the above data.

$$E_{req(x)} = E_{i(x)} \times HH \tag{5}$$

where $E_{req(x)}$ = energy requirements of energy service (x) in rural/urban area (kWh)

$E_{i(x)}$ = energy intensity of energy service (x) (kWh/household) [64]

HH = Number of households in rural and urban areas with access to energy service

The National Energy Efficiency Strategy (NEES) target of 10% residential energy efficiency improvement by 2015 relative to a baseline projected from 2000 [65] was adopted in quantifying the changes in the energy efficiency of household appliances and energy services from 1990 to 2014, and 2016 to 2099, by assuming a 10% energy efficiency improvement every 15 years.

Table 6. WEAP model calibration and validation statistics performed by Dlamini et al. [27] for observed streamflow retrieved from DWS [67] and simulated streamflow using the CHIRPS historical dataset and global circulation model's average precipitation's ensemble for the period 01/01/1990 to 31/12/2018.

		CHIRPS	RCP4.5	RCP8.5
Calibration Statistics	*d*	0.958	0.860	0.836
	nRMSE (%)	22.32	40.77	44.25
	PBIAS	-22.54	-19.62	-24.17
	R^2	0.902	0.7614	0.805
Validation Statistics	*d*	0.790	0.951	0.832
	nRMSE (%)	5.51	2.674	4.933
	PBIAS	18.43	8.940	16.49
	R^2	0.905	0.988	0.987

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Model interactions and data analysis statistics. After quantifying energy use by irrigation and households (MWh/annum), they were manually transferred into the WEAP model, as observed in the methodology's flow chart shown in Fig 2. Since the LEAP model cannot simulate the water requirements for energy generation per kWh, a value of 1100 litre/MWh, which is the average water use of the Majuba power station [66], was computed as the annual water use rate for energy generation. As a result, the WEAP model simulated and projected the total water supply requirements, considering the variations in household, irrigation, and energy generation requirements.

As the WEAP model is the central model in this assessment, it was calibrated against historical streamflow observations for the period 01/01/1990 to 31/12/2019. The calibration and validation processes, including data used, the respective sources and outcomes, are detailed in the Dlamini *et al*. [27] study and presented in Table 6, therefore they are not repeated in this current study. Descriptive statistics (means, percent increases relative to the historical scenario and coefficients of variation) were employed to analyse the output of the WEAP, LEAP and gAEZ models.

Results and discussion

As discussed in the previous sections, results from the CPA are detailed in the Dlamini *et al*. [27] study and are summarized in the *Current Practice Approach* section of this study. It should be stated that, because the computational methods and input data used are the same, the historical and projected values of precipitation, evapotranspiration, and household water demands' values under the CPA and CLEWS approaches are consistent. Hence, the water systems outputs (surface runoff and water availability) established under the different computations of energy and irrigation water demands using the CLEWS approach are compared to those established under the CPA to see if the CLEWS modelling approach brings upon any significant differences. Furthermore, the demand site coverage and water supply system's reliability results under both CPA and CLEWS, which are the focus of the current paper, are presented and compared in this section.

Surface runoff

The surface runoff at the Buffalo River's outlet (*Q*) projected from the CPA and CLEWS approaches displays differences throughout the 21st century. CLEWS projected *Q* values, which are, on average, 8.5% lower than those projected by the CPA approach under both climate scenarios, thus flagging increased water usage and/or storage within the water supply system. Nonetheless, as seen in Table 7, average *Q* volumes are still anticipated to increase under

Table 7. Historical, near-, mid-, and far-future projections of surface runoff in the Buffalo River catchment (Mm^3/annum).

Study Period	Surface Runoff at the Buffalo River Outlet			
	RCP4.5		RCP8.5	
	CPA	CLEWS	CPA	CLEWS
Historical (1990–2019)	3330	3026	3382	3080
Near future (2020–2045)	3336	3033	3318	3024
Mid-future (2046–2070)	3341	3045	3765	3468
Far future (2071–2099)	3566	3266	3815	3523

https://doi.org/10.1371/journal.pclm.0000464.t007

CLEWS for both RCP4.5 and RCP8.5 climate change scenarios. The projected increase in *Q* reflects the expected rainfall increases throughout the study period. This finding agrees with the results of Ndlovu *et al.* [68], who projected increased surface runoff in the KwaZulu-Natal province, South Africa, due to increased extreme rainfall events, i.e., days with 20 mm or more precipitation. A review undertaken by Kusangaya *et al.* [69] highlights that a general decrease in runoff is expected in Southern Africa; however, in high-rainfall regions like the uThukela River catchment, where the Buffalo River catchment is located, Kusangaya *et al.* [69] also mentioned that increases in surface runoff are to be expected. Likewise, in the high-rainfall Kabompo River basin, Zambia, Ndhlovu and Woyessa [70] also projected increased runoff by 5% and 6% under RCP4.5 and RCP8.5, respectively.

Water demands

Irrigation water requirements. When compared to the CPA's irrigation water requirements per hectare (IWR/ha), which were assumed equivalent to the historical IWR/ha values, projections of IWR/ha using the CLEWS gAEZ approach increase on average by 30% throughout the 21st century, as seen in Fig 7. These results are expected given that several studies investigating IWR in South African catchments [71–73] have presented increasing trends under climate change due to increased crop water requirements from temperature increases and changing rainfall patterns.

However, the suitable hectares (ha) for irrigated crop production projected by the gAEZ assessment, also shown in Fig 7, show a declining trend under both RCP4.5 and RCP8.5 scenarios by an average of -0.4%, especially maize and soybean, which is attributable to the projected increased extreme rainfall events. These findings have been reported in several studies worldwide [74–77]. Irrigation generally reduces the negative effects of temperature changes [78, 79] thus, unlike rainfed crops, land suitability for irrigated crop production is more sensitive to water availability changes brought upon by increased precipitation fluctuations and/or decreases in average rainfall [78]. Similarly, a study conducted in sub-Saharan Africa by Chapman *et al.* [80] also established that while precipitation increases projected by climate models indicated increased suitability for maize and soybean, a significant reduction in crop suitability is noted when climate projections consist of a high frequency of extreme rainfall events.

As a result of the decreases in irrigated crop suitability in our study, the total volume of IWR projected using the CLEWS approach, in comparison to the CPA approaches results, are lower by 17% and 19% in the mid-and far future under RCP4.5, and lower by 16% and 12% for the above-mentioned periods under RCP8.5, respectively. These results are unexpected given the previously discussed increases in IWR/ha and the consensus that irrigated agriculture is likely to strain water resources in South Africa further [81]. However, unlike the Buffalo River catchment, regional climate change projections in South Africa show slight decreases to no

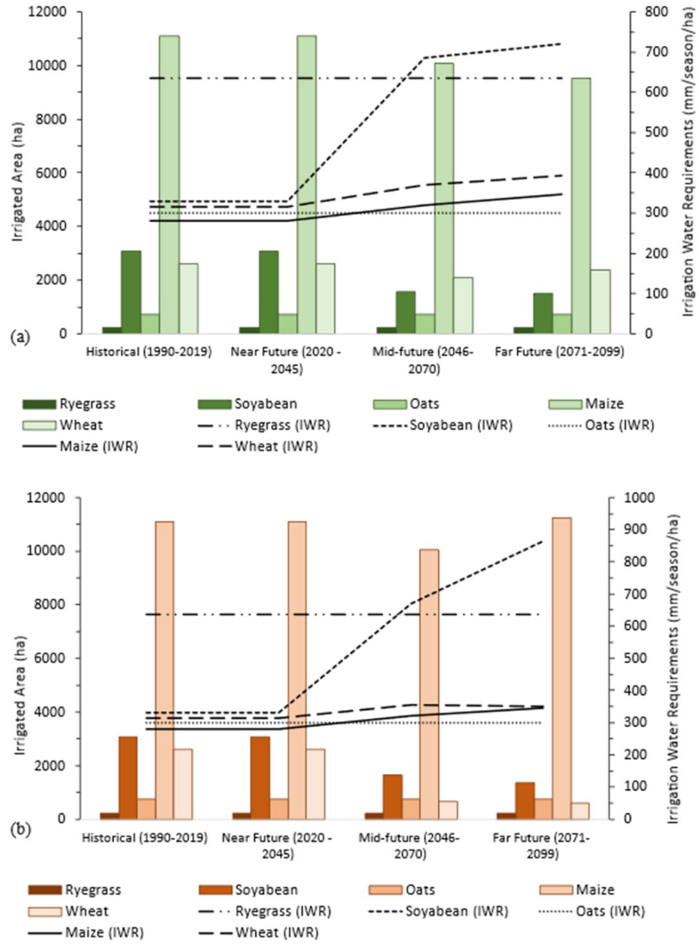

Fig 7. Historical and projected (near-, mid- and far future) irrigated areas and irrigation water requirements of ryegrass, soybean, oats and maize in the Buffalo River catchment, derived using the food and agriculture organization's global agro-ecological zones assessment (https://gaez.fao.org/) under (a) RCP4.5 and (b) RCP8.5 climate change scenarios.

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changes in rainfall averages and extreme events [82], which could be why irrigated agriculture is generally expected to increase. As much as the reduction in total IWR will ease the pressure on the water supply system in the Buffalo River catchment, the decreases in land suitability for crop production indicate looming food security issues.

Energy generation water demands. From Fig 8, the household energy demands projected using the CLEWS approach are anticipated to increase under climate change. The Newcastle local municipality contributed the most to this expected increase (0.36 million MWh/annum in 1990 to 1.25 million MWh/annum in 2099), attributable to its large and fast-growing population. Irrigation energy demands increased to 2 million MWh in 2099 under both climate scenarios, mainly due to the Nquthu local municipality's agricultural production (see S9 Fig to S12 Fig in the Annexure). Fluctuations of the irrigation energy demands significantly impact total energy demand variations. To support this observation, the coefficient of determination (R^2), which indicates the degree of similarity between observed and simulated data [83], was calculated for household and irrigation energy demands against total energy demands and found to be 0.993 and 0.987, respectively, with the R^2 plots in S13 Fig in the Annexure.

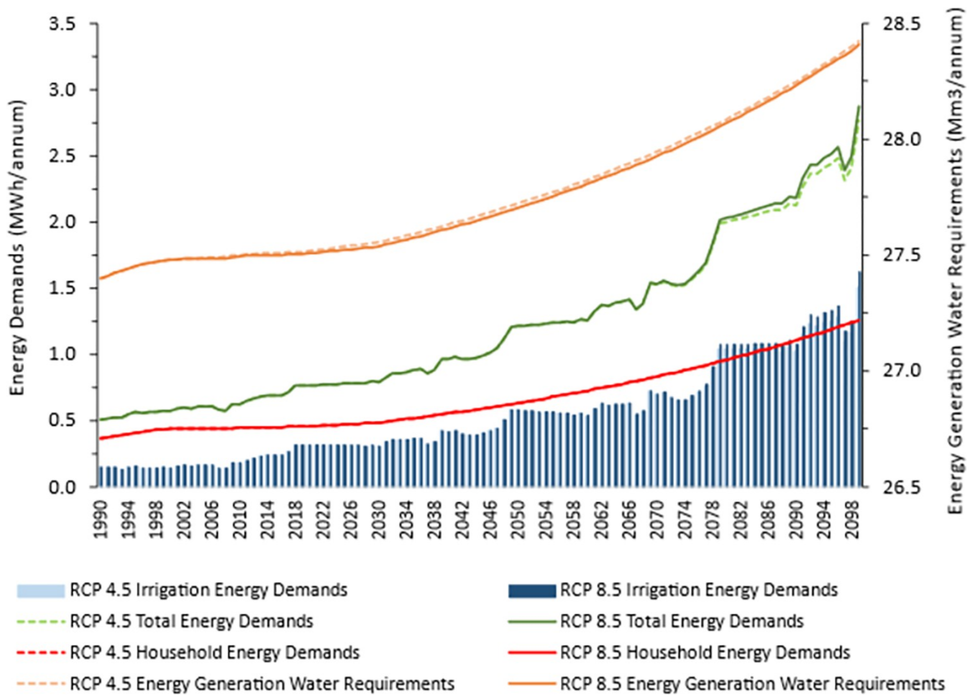

Fig 8. Historical and projected energy demands (MWh/annum) and energy generation water requirements (Mm^3/annum) under the RCP4.5 and RCP8.5 climate change scenarios in the Buffalo River catchment throughout the study period (01/01/1990-31/12/2099).

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The CPA method only considered the Majuba power station's water demands for energy generation. As such, the Zaaihoek Water Transfer Scheme's 3 m^3/second transfer to the Majuba power station, equating to 27 Mm^3/annum of the catchment's water supply, was dedicated to power generation. In the CLEWS approach, when supplementing this demand with water required to generate household and irrigation energy, water requirements for total energy generation increase to a maximum of 28.5 Mm^3/annum at the end of the 21st century. Such minimal water demands from the energy sector are anticipated as energy generation in South Africa consumes approximately 5% (inclusive of coal mining) of the total water supply [84].

Total water demands. The results on the projected CPA and CLEWS RCP4.5 and RCP8.5 total water supply requirements presented a notable gap, as seen in Table 8, caused by the IWR results. After the incorporation of changes in attainable agricultural yields and their respective reduced overall IWR, a consequential reduction of the CLEWS total water supply requirements resulted. This is also in line with the national statistics of water use by sectors, which indicate that agriculture and irrigation are largely responsible for, and influence the trends of, water resource consumption in South Africa [85].

Reservoir storage changes and unmet demands

The net reservoir storage (S_N) projected under CLEWS is similar to those modelled using the CPA approach, as per Fig 9, with mean values of 275 Mm^3/annum (standard deviation is 37.8) and 268 Mm^3/annum (standard deviation is 36.4) under RCP4.5 and RCP8.5 scenarios, respectively. Such results are expected as no changes were made to the reservoir operational rules in the CLEWS approach.

Table 8. Total water supply requirements (Mm^3/annum) in the Buffalo River catchment under all scenarios from period 01/01/1990–31/12/2099.

Study Period	Modelling Scenario	Minimum	Median	Mean	Maximum
Historical	CPA	151.3	153.4	153.2	154.6
	CLEWS RCP4.5	151.4	153.6	153.3	154.8
	CLEWS RCP8.5	151.4	153.6	153.3	154.8
Near Future	CPA	154.7	156	156	157.2
	CLEWS RCP4.5	154.9	156.2	156.2	157.5
	CLEWS RCP8.5	154.9	156.2	156.2	157.5
Mid-future	CPA	157.3	158.5	158.5	159.8
	CLEWS RCP4.5	151.2	154.2	154.3	157.3
	CLEWS RCP8.5	151.3	154.3	154.3	157.3
Far Future	CPA	159.9	161.3	161.3	162.7
	CLEWS RCP4.5	151.3	152.5	152.5	153.7
	CLEWS RCP8.5	151.5	154.1	154.1	156.8

https://doi.org/10.1371/journal.pclm.0000464.t008

In addition, for both CPA and CLEWS, the variability of projected S_N values under both RCP4.5 and RCP8.5 scenarios show increases, especially in the mid-and far-future by 6% to 10%, respectively. Given the projected surface runoff (Q) increases of, on average, 14% per annum in the mid- and far-future timeframes, the above-mentioned increases in S_N are low. This inadequate capture and storage of water supplies are assumed to be caused by water storage capacity restrictions. Thus, this observation emphasizes that the Buffalo River catchment's water infrastructure substantially limits water supply improvements, rather than the effects of climate change, which provide an opportunity for boosting water supply. These findings are dissimilar to Strydom *et al.* [86] projections of reduced rainfall and streamflow in the uMgeni

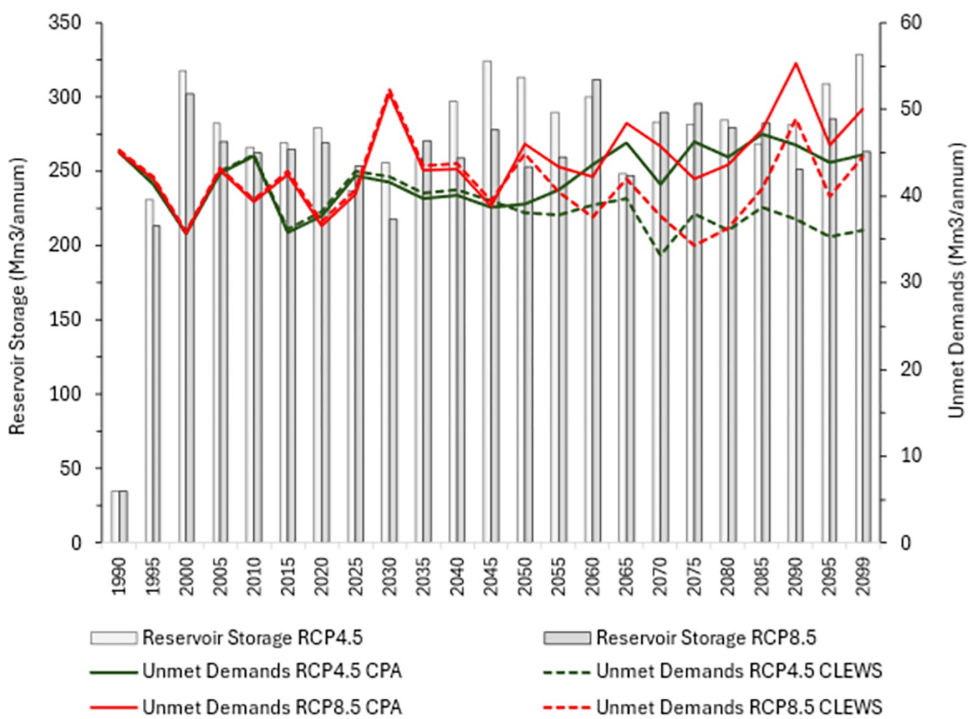

Fig 9. Simulated and projected annual reservoir storage (Mm^3/annum) and unmet demands (Mm/annum) in the Buffalo River catchment using the CPA and CLEWS approach for the period 01/01/1990 to 31/12/2099.

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catchment, KwaZulu-Natal, South Africa, propelling reduced available stored water. However, in their finding, Strydom *et al*. [86] also highlighted that the uMgeni catchment's reservoir operating rules are highly likely to strain water capture and storage under climate change.

Even though the projected S_N values are similar in both CPA and CLEWS approaches, CLEWS' projected unmet demands are lower by 9% and 16% in the mid- and far-future timeframes, respectively. The lower unmet demands simulated using CLEWS correspond to the anticipated declines in total IWR and in the mid- and far-future timeframes, which decreases total water requirements to be met.

Demand site coverage

The demand site coverage (*Dcov(%)*), defined as the percentage of demands met per demand site, was analysed for local municipalities as they are the primary demand sites, i.e., water is ultimately transmitted to them for domestic, energy and agricultural purposes. From Fig 10, the annual *Dcov(%)* for each local municipality are different, this being a result of the water allocation plans of the Buffalo River catchment's water supply system.

Historical demand site coverage. The Newcastle and Dannhauser local municipalities' demands are highly prioritized regarding water distribution, with simulated mean historical *Dcov(%)* values being 96% and 99%, respectively. However, the Utrecht and Nquthu local municipalities' historical maximum *Dcov(%)* being 7% and 11%, respectively, indicates a relatively low prioritisation of these local municipalities' water demands by the current water allocation plans. This issue of water supply provision being better in urban areas than in rural communities has been noted to be a plague within southern African regions [87]. In Zambia, rural areas similarly have more than 70% lower odds of meeting their water demands than urban areas [88].

Differences between demand site coverage projected by CPA and CLEWS. When the *Dcov(%)* values projected by the CPA and CLEWS approaches are contrasted, the CLEWS *Dcov(%)* is significantly higher in the Dannhauser and Newcastle local municipalities,

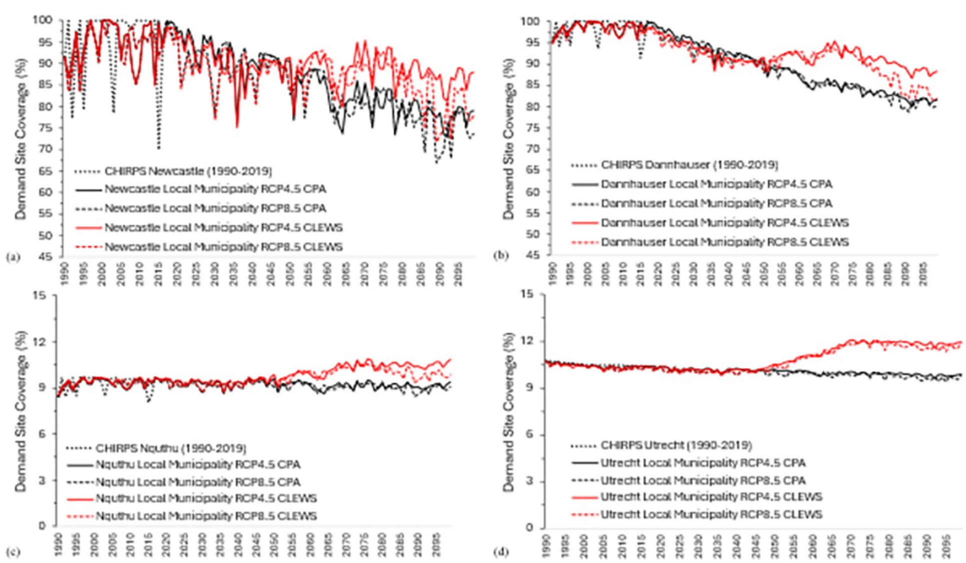

Fig 10. Annual demand site coverage (%) of the following local municipalities in the Buffalo River catchment: (a) Newcastle (range = 67% to 100%), (b) Dannhauser (range = 80% to 100%), (c) Nquthu (range = 8% to 11%) and (d) Utrecht (range = 9.5% to 12.5%), under the RCP4.5 and RCP8.5 climate scenarios, established using the CPA and CLEWS approaches, for the period 01/01/1990–31/12/2099.

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Table 9. Shapiro-Wilk normality test results of local municipalities' projected demand coverage under the RCP4.5 and RCP8.5 climate change scenarios, derived using the CLEWS approach.

Study Period (Years)	Climate Scenario	Shapiro-Wilk test P-value (Passed Normality Test (α ≥ 0.05)?)			
		Newcastle	Dannhauser	Utrecht	Nquthu
Near Future (2020–2045)	RCP4.5	0.007 (No)	0.610 (Yes)	0.003 (No)	0.015 (No)
	RCP8.5	0.297 (Yes)	0.717 (Yes)	0.037 (No)	0.917 (Yes)
Mid-Future (2046–2070)	RCP4.5	0.049 (No)	0.911 (Yes)	0.382 (Yes)	0.759 (Yes)
	RCP8.5	0.046 (No)	0.168 (Yes)	0.289 (Yes)	0.368 (Yes)
Far Future (2071–2099)	RCP4.5	0.315 (Yes)	0.644 (Yes)	0.129 (Yes)	0.538 (Yes)
	RCP8.5	0.213 (Yes)	0.054 (Yes)	0.230 (Yes)	0.662 (Yes)

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particularly in the Newcastle local municipality; in the mid- and far-future timeframes, CLEWS *Dcov(%)* for Newcastle is higher by 5% and 10%, respectively. Therefore, this further proves that the Buffalo River catchment's water system's functionality and allocation plans are centred around meeting the water demands of the Newcastle and Dannhauser local municipalities, making them high-priority demand sites, and enabling these sites to maintain a *Dcov(%)* above 70%, even under worsened climate change conditions. The domestic and energy sectors benefit substantially from this as a minimum of 76% of their water requirements emanate from high-priority demand areas, thus yielding a maximum of 30% of their water demands not being met under climate change.

For the Nquthu and Utrecht local municipalities, *Dcov(%)* remains below 12% under climate change, reinforcing that these are low-priority water supply regions. With over 65% of the agricultural sector's water demands stemming from these low-priority regions, it is expected that an average of 90% of irrigation water demands in these regions will not be met, equating to approximately 60% and 65% of the catchment's total IWR not being met under the RCP4.5 and RCP8.5 scenarios, respectively. Similar results are highlighted in a study by Nhemachena *et al.* [89], who stated that water scarcity, increased demand, and competition from other water users will reduce agricultural productivity by 50% or more in South African regions, as well as other western parts of southern Africa including Botswana, Namibia, and Zambia, by 2080.

Differences in projected water demand coverage for RCP4.5 and RCP8.5 scenarios. To check for significant differences in the CLEWS *Dcov(%)* under the RCP4.5 and RCP8.5 scenarios, the local municipalities' *Dcov(%)* outputs were analysed with the statistical Welch test for parametric t-tests and the Mann-Whitney test for non-parametric t-tests [90], upon verification of normality using the Shapiro-Wilks test [91]. Moreover, the significance level (α) for the t-tests was set at 5% to ensure that, in cases where the significance level has been surpassed, the null hypothesis (no difference in means) is rejected. The results are tabulated in Tables 9 and 10.

From Table 10, the differences in *Dcov(%)* values are only significant in the near- and far-future timeframes, with the differences in the mean *Dcov(%)* values (RCP4.5 mean value–RCP8.5 mean value) per local municipality range from -0.02 to -0.84 in the near future, and -0.21 to -3.91 in the far-future. This highlights that under the RCP8.5 scenario, the water demands that can be covered in each local municipality are expected to be lower than those anticipated under the RCP4.5 scenario, hence flagging concerns related to the reliability of the water supplies during these timeframes.

Reliability of water system

The WEAP model projected the reliability of the Buffalo River catchment system in providing its water demands per demand site, as observed in Fig 11. From Eq (6), reliability (*RE(%)*) is

Table 10. Inferential statistics comparing the significant differences in projected demand site coverage results per local municipality in the Buffalo River catchment, obtained under the RCP4.5 and RCP8.5 scenarios.

Study Period (Years)	Local Municipality	P-value	Significant difference?	Differences in means (RCP4.5—RCP8.5)
Near Future (2020–2045)	Newcastle	0.1355	No	-0.84
	Dannhauser	0.0488	Yes	-0.28
	Utrecht	0.0374	Yes	-0.285
	Nquthu	0.1361	No	-0.015
Mid-future (2046–2070)	Newcastle	0.74	No	-0.03
	Dannhauser	0.9419	No	0.18
	Utrecht	0.3303	No	-0.1224
	Nquthu	0.6786	No	-0.0248
Far Future (2071–2099)	Newcastle	0.0048	Yes	-3.908
	Dannhauser	0.1453	No	-0.43
	Utrecht	0.0171	Yes	-0.2862
	Nquthu	<0.0001	Yes	-0.21

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calculated as the percentage of timesteps in which the demand side was fully satisfied, i.e., 100% *Dcov(%)* [92].

$$RE(\%) = \left({}^{T} - T_D/_{T}\right) \times 100 \qquad (6)$$

where *RE(%)* = reliability index of demand site (%)
T = total number of years of respective timeframe
T_D = total number of years where demand site *Dcov(%)* $\neq$ 100%

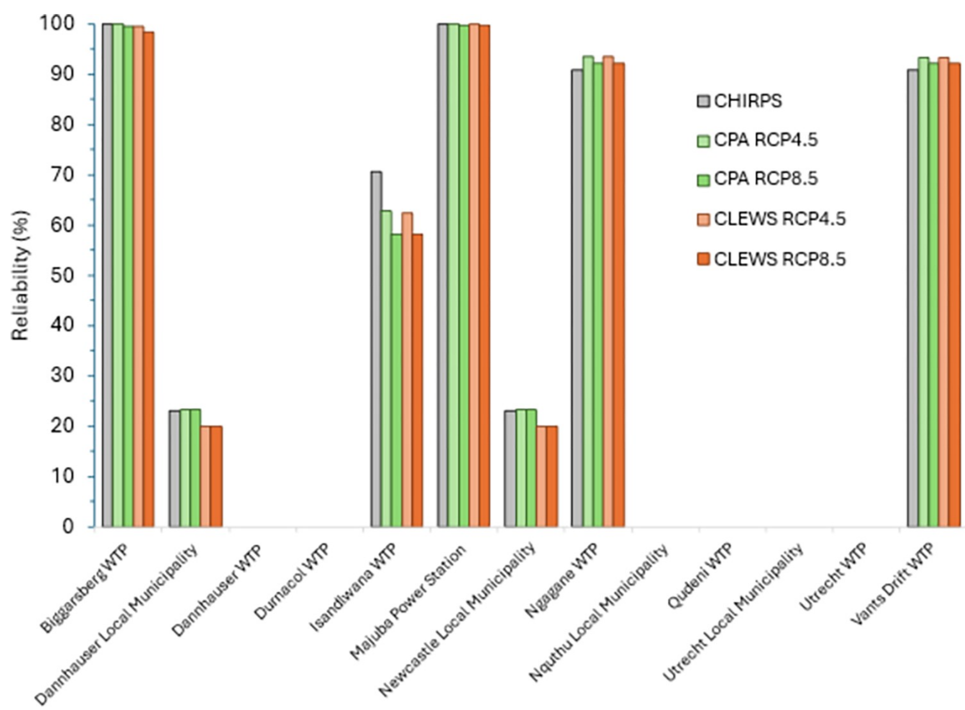

Fig 11. Water system supply reliability (%) for the Buffalo River catchment's water treatment plants (WTP), local municipalities and the Majuba power station's water provisions throughout the study period (01/01/1990-31/12/2099).

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Demand sites that yielded high *RE(%)* of over 50% include the Majuba power station, Biggarsberg WTP, Isandlwana WTP, Ngagane WTP and the Vant's Drift WTP. The Majuba power station is the only demand source extracting water from the Zaaihoek Water Transfer scheme via the Zaaihoek Dam, located in the upper regions of the Buffalo River catchment. As such, this provides a reason for the high *RE(%)*. The Biggarsberg, Isandlwana, Ngagane and Vant's Drift WTPs' first supply preferences are primary demand sites, and as such, their demands for transmission are met first, hence their high *RE(%)* values. To elaborate, the Qudeni WTP is a secondary supply preference for the Nquthu local municipality, whereas the Vant's Drift WTP is the primary supply preference, which is why Qudeni's *RE(%)* value is 0% while Vant's Drift is 93%.

In noting the impacts of climate change on *RE(%)*, an average reduction of 2% and 4% is noted when comparing the historical *RE(%)* to that of the CLEWS under the RCP4.5 and RCP8.5 scenarios, respectively. This decline in reliability under climate change is unexpected given the reduced water demands, and it is assumed to be resulting from the increased frequency of extreme rainfall events, which also alter the temporal surface water storage and supply in the same pattern. Given this, it is evident that the relationship between water supply is affected by temporal climatic changes, as reported in several studies across the globe; for example, in Morocco's Middle Draa Valley and Cambodia's Tonle Sap Lake, drought conditions are anticipated under climate change and are consequently predicted to alter water storage and increase the gap between water supply and demand [93, 94]. Similar to our study's findings, the Pozzillo Reservoir in Sicily, Italy, is anticipated to experience increased rainfall under climate change; however, despite these increases, reductions in reservoir temporal reliability are projected, especially under the RCP8.5 scenario, as a result of increased frequency of extreme weather events, thus aggravating increases in water supply deficit [95].

When comparing the primary demand sites' *RE(%)* values, the Newcastle and Dannhauser local municipalities' *RE(%)* decreases by 3% under the CLEWS approach and climate change conditions. However, the *RE(%)* remains above 20%. This is owing to them being high-priority sites and having multiple supply points, which increases the stability of their *RE(%)*. The increases in *Dcov(%)* for the Nquthu and Utrecht local municipalities, however, proved to be insignificant as their CLEWS *RE(%)* values are 0%, i.e., their annual water demands are projected not to be fully supplied throughout the projection period, i.e., $Dcov(\%) \neq 100\%$. Therefore, these results similarly demonstrate the sentiments echoed in the demand site coverage section, indicating that the correlation between water supply and demand in domestic and energy sectors is notably stronger compared to the food (agricultural) sector. Given this poor demand coverage and the unreliability of water supplies to meet demands from the agricultural sector, this highlights and supports the statement made by Simpson *et al.* [10] on the limited integration of WEF nexus principles into current WEF resource management strategies in South Africa.

Several studies have also flagged the inadequate supply of agricultural water demands multiple climate change scenarios [3, 7, 96–98] and propose implementing measures to enhance the resilience of agricultural systems, such as promoting water-efficient eco-friendly farming practices, managing water pollution, and increasing biodiversity through crop rotation and revegetation efforts. In addition to these interventions, it is imperative for future planning and management of water resources to extend beyond the water-energy nexus thinking. For the Buffalo River catchment, this involves enhancing water storage capacities, capitalizing on the expected increase in surface runoff due to climate variations, and improving water allocation to optimize agricultural productivity, particularly for crops like maize and soybean.

Study limitations

The modelling approach's limitations include the use of statistically downscaled (SD) climate change projections were used. The computation of SD projections is heavily based on the observed relationship between large-scale atmospheric variables and local or regional climate variables. Due to the Earth's system being nonlinear, a statistical relationship that was held in the past may not apply in the future. Thus, SD methods not accounting for natural climate fluctuations could cause non-representative results in climate projections. Additionally, data limitations enabled only surface water and the primary water consumers in the catchment (household, irrigation, and energy production) to be accounted for. Therefore, there is a possibility of error in the quantified water supply-demand relationship. Despite these potential limitations, the model validation process produced satisfactory results.

Conclusions and recommendations

Understanding the effects of climate change on water, energy, and food resources is crucial for developing sustainable water management policies, given the interconnectedness of these resources. Therefore, this study successfully employed the CLEWS modelling framework, incorporating tools like WEAP, LEAP, and gAEZ, to evaluate how climate change impacts the balance between water supply and demand across domestic, energy, and agricultural (irrigation) sectors in the Buffalo River catchment, KwaZulu-Natal, South Africa. The findings contribute to South Africa's dearth of knowledge on the WEF nexus and illustrate how WEF nexus thinking can be applied to water resource management in South African catchments.

This study was premised on the null hypothesis of climate change not influencing the relationship between water supplies and demands. However, in conclusion, we reject the null hypothesis. The following shifts in key factors (sectors) influencing water demands and supplies in the Buffalo River catchment are anticipated under climate change:

a. Increased surface water storage is anticipated under climate change due to increased surface runoff. However, this surface water supply increase is expected to be negligible, primarily due to the constraints posed by insufficient water storage infrastructure and the catchment's water distribution plans.

b. Land suitability for agricultural production is expected to decrease under climate change in the Buffalo River catchment, thus propelling the summative values of irrigation water demands also to decline.

c. Increased water demands from domestic and energy generation were projected under climate change. However, the decline in irrigation water requirements poses a significantly greater influence on the total water requirements of the Buffalo River catchment—the overall decline of the total requirements observes this.

Due to the expected increased rainfall variability in the Buffalo River catchment, the capability and reliability of the water supplies to meet demands are anticipated to decline under climate change as we tend towards the end of the 21st century, despite the above-mentioned expected increases in water supply and decreases in total water demands. With domestic and energy-intensive sites (Newcastle and Dannhauser local municipalities) being high-priority for water supply, the low-priority regions with extensive agricultural production (Nquthu and Utrecht local municipalities) are primarily affected by this decline in water supply reliability. The inequality in water supply distribution, propelled by the reduced land suitability for crop production under climate change, poses a critical concern for food security and the socioeconomic standing of the catchment communities. Moreover, if not curtailed, the anticipated decline in water resource reliability could perpetuate unsustainable water management practices, prompting individuals to extract and utilise untreated water sources. This not only deteriorates water resources but also increases the risk of water-related health concerns.

In essence, our research findings highlight that the balance between water supply and demand is highly sensitive to climate change and resource management. Thus, improving the relationship between water supply and demand under climate change entails strengthening water infrastructure reliability and allocation plans. In doing so, it is advisable to consider water supply infrastructure as a service rather than merely a facility. Thus, future water resource plans should not focus only on expanding water storage but also on optimizing the provision rate by adjusting water transmission and diversions during periods of system failure, especially in low-priority regions. This can be executed by redirecting some water transmission links from the high-priority demand sites to Utrecht and Nquthu and re-establishing the operational rules of WTPs, especially the Utrecht WTP.

The effectiveness of both the WEAP and LEAP models hinges on the quantity and detail of the data they utilize. Therefore, it is strongly recommended that future research uses high-quality data in these models' simulation processes. This includes, for example, employing dynamically downscaled precipitation projections, which offer higher resolution compared to statistically downscaled data, and incorporating the latest CMIP6 GCM climate output data. However, it is worth noting that the bias-correction method employed in deriving precipitation estimates from the statistically downscaled data, as evidenced by the WEAP model performance evaluation, provided adequate precipitation values that accurately reflected the hydrology of the catchment area.

Since this study is limited by the exclusion of groundwater as a water source, it is suggested that future research should concentrate on gathering detailed quantitative data on groundwater availability, consumption patterns, and energy usage for household and irrigation purposes within the Buffalo River catchment. Given the significance of groundwater utilization in climate change adaptation, incorporating groundwater data would enable the conjunctive use of both ground and surface water resources, thereby enhancing the overall understanding and management of water resources in the catchment area.

The CLEWS framework effectively illustrates the intricate relationships among the Buffalo River catchment's water, energy, and food resources. Therefore, due to its dynamic structure, the use of this framework is encouraged for studies investigating the impacts of climate change on the WEF resources and other sectors as well such as health, environment and biodiversity, termed the "WEF+" nexus, given that the incorporation of the other sectors is done in a scientifically sound manner. The study's results can serve as valuable reference points for future research on the climate change-water-energy-food nexus, enabling policymakers and decision-makers better to understand climate change's effects on these resources and evaluate the sustainability of current water and catchment management plans in light of climate change.

Supporting information

S1 Table. Irrigation water requirements for each dominant crop grown in the Buffalo River catchment [47, 48].
(XLSX)

S2 Table. Average energy consumption of electric appliance/energy service in kWh per income group for the year 2015 [64].
(XLSX)

S1 Fig. Planted hectares in the Buffalo River catchment's local municipalities [42].
(TIF)

S2 Fig. Irrigated commercial crop production yields in the Buffalo River catchment's local municipalities (kg/ha) [42].
(TIF)

S3 Fig. Thus figure shows the production in kg/ha of commercial crops in the Buffalo River catchment's local municipalities [42].
(TIF)

S4 Fig. Households by main source of energy for cooking [56].
(TIF)

S5 Fig. Households by main source of energy for heating(refrigeration) [56].
(TIF)

S6 Fig. Households by main source of energy for lighting [56].
(TIF)

S7 Fig. Households by main source of energy for water heating [56].
(TIF)

S8 Fig. Households by main source of energy for space heating [56].
(TIF)

S9 Fig. gAEZ projected irrigated area per local municipality under RCP 4.5 scenario.
(TIF)

S10 Fig. gAEZ projected irrigated area per local municipality under RCP 8.5 scenario.
(TIF)

S11 Fig. LEAP irrigation energy demands (MWh/annum) per local municipality in the Buffalo River catchment under the RCP4.5 scenario.
(TIF)

S12 Fig. LEAP irrigation energy demands (MWh/annum) per local municipality in the Buffalo River catchment under the RCP8.5 scenario.
(TIF)

S13 Fig. Comparison of irrigation energy demands, and the total energy demands throughout the projection period (01/01/2020–31/12/2099) under the (a) RCP4.5 scenario and (b) RCP 8.5 scenario.
(TIF)

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