Climate change in South African rivers: A case study on the Olifants River in the Kruger National Park

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Freshwater systems are among the most endangered ecosystems, with anthropogenic climate change causing detrimental ecological and economic impacts. Due to climate change, increased air temperatures will translate into the warming of rivers, and at the same time will alter flow regimes and increase evaporation and stochastic events. In this study, we used validated statistical water temperature models that predict average water temperatures (WT_{avg}) from air temperature to project monthly and daily WT_{avg} from 2025 to 2100 CE in the heavily polluted and over-abstracted Olifants River, Kruger National Park, Limpopo Province, South Africa, under the ‘business as usual’ Representative Concentration Pathway 8.5 scenario. The results from 16 General Circulation Models showed that monthly WT_{avg} is likely to increase by 3.6 °C and showed summer months reaching up to 34–35 °C by 2100 CE. The daily results showed a similar increase of 3.7 °C by 2100 CE, with some extreme days reaching 42–44 °C. These results support similar research conducted within the Olifants catchment of the Limpopo Basin and add to the limited knowledge of freshwater climate change, especially in Africa. Climate change will ultimately alter the thermal and physical landscape of the Olifants River and this forecast highlights the need for further research on the potential detrimental consequences on freshwater biota, including possible local extinctions.

Significance:

- Increasing air temperature due to anthropogenic climate change will cause water temperatures to rise.
- Statistical models can be used to predict future water temperatures from air temperature.
- The projections show an increase in monthly average water temperature (WT_{avg}) of 3.6 °C and an increase in daily WT_{avg} of 3.7 °C by the end of the 21st century.
- This drastic rise in water temperatures will ultimately have negative effects on freshwater biota.

Introduction

Freshwater systems are under severe pressure from direct and indirect anthropogenic effects that include pollution, habitat degradation, exotic species introductions, over-exploitation, mining, flow regime and river morphology modifications, and climate change.[1-10] These disturbances are occurring in conjunction, and the compounding impacts on freshwater systems can be devastating.[11-13] For example, alterations to the hydrology or river-associated habitats can facilitate successful species invasions due to changes in habitat and water quality.[14] Land degradation such as deforestation due to mining and agriculture can exacerbate soil erosion and reduce infiltration, increasing surface run-off which causes severe flooding during extreme weather events caused by climate change.[12,15]

Due to these cumulative impacts, along with the rise in the human population and consequent demand for resources, freshwater systems are considered one of the most vulnerable ecosystems.[3,16] Freshwater systems have provided humans with important goods and services, and, because of their linear nature, any transverse or longitudinal disturbance causes cascading effects both upstream and downstream.[17] In the Danube Basin in Europe, for instance, a hydroelectric power plant built to supply energy to southeastern Europe modified freshwater ecosystems to such a degree that it resulted in changes in flow regime and habitat and disconnected floodplains, and with an increase in energy demand due to human population growth, these changes are likely to be exacerbated.[18,19]

Freshwater systems are particularly vulnerable to the effects of climate change as they are exposed to anthropogenic stressors, which leads to a loss of connectivity between freshwater patches, and are also disproportionately exploited considering that they cover only 0.8% of the earth’s surface area.[20] The effects of climate change on freshwater systems are not only translated into a rise in water temperature, but also into changes in nutrient load and primary productivity, acidification, salinisation, eutrophication, flow regime and more frequent extreme weather events such as flooding.[21-23]

Rivers in the southern African subregion are likely to be more affected by climate change than in other regions because their global mean annual average near-surface temperatures are set to increase by 2–3 °C by the end of the 21st century, while mean air temperatures are predicted to rise by 4–7 °C[24-26], with maximum air temperatures predicted to increase by 4–8 °C by 2100 CE under low mitigation scenarios[26,27]. Evaporation rates in southern Africa are as high as 65%, which decreases effective rainfall to a subregion that is already prone to frequent droughts and will experience a decrease in precipitation in the future.[28-30] Projections of annual reference crop evaporation in South Africa show that by 2100 CE, there will be increases of 15–20% in the far interior and 20–25% along its western, southern and eastern borders.[31] Along with further water extraction, this can lead to altered flow regimes and to perennial systems becoming intermittent streams, and eventually drying up in the absence of proactive adaptive management measures.[28-30] Freshwater biota, such as fishes and macroinvertebrates, rely on specific flow regimes for breeding and survival, and have very specific thermal niches, and disruptions to these parameters can be detrimental to the ecology of freshwater systems.[10,32,33]

The prediction of future water temperature scenarios in South Africa has previously been based on a statistical linear regression model developed by Rivers-Moore et al.[34] which established that water temperature can be simulated using air temperature. The model also established that the thermal properties of South African rivers may differ from those of other regions, and a linear regression model was developed and tested on rivers in the country.[34,35]

The aim of this study was to simulate future water temperatures from 2025 to 2100 CE and to investigate the effects of future air temperatures on the water temperatures in southeastern Africa based on the Olifants River in the Kruger National Park (KNP), in the Limpopo Province of South Africa, under the ‘business as usual’ Representative Concentration Pathway (RCP) 8.5 scenario as a case study. This river is an example of a freshwater system that is already heavily impacted by pollution and over-abstraction[36,37] and is likely to be even more impacted than those in other regions globally. While there have been studies on future climate change scenarios within the Olifants River Basin, many of these studies were conducted on the entire Olifants Basin, not on one particular river, and, more importantly, did not take into account the change in water temperature but instead were based on air temperature.[38,39] While water and air temperatures provide an important baseline for the present study, a more focused investigation on water temperature within the river is essential for understanding the ecological impacts on freshwater ecosystems.

The KNP is already facing many challenges of water management due to pollution in rivers from upstream and other anthropogenic disturbances.[40] The warming of these rivers, along with other stressors such as decreased run-off, decreased precipitation and increased water-use by humans will lead to the loss of habitat and heat stress which subsequently will result in mass die-offs and extinctions of the aquatic fauna, as well as water stress to the animals within KNP that rely on these rivers as water sources. It is predicted that with rising air temperatures to the end of the 21st century, both average monthly and daily water temperatures of the Olifants River will also increase, which will ultimately have a negative effect on the aquatic fauna of this river. Impacts on the Olifants River will likely manifest in other rivers in the Olifants River Basin, and even the broader Limpopo River Basin, as the region faces similar climate change forecasts.

Methods

The Olifants River Catchment is ~75 000 km², expanding across South Africa and Mozambique.[41] It is an important tributary of the larger Limpopo Basin that spans across four countries.[37] The Olifants River is a perennial river that runs through the KNP which represents the largest protected area in South Africa and contributes substantially to tourism within the region, while supplying water to both South Africa and Mozambique.[40,42] It represents approximately 6% of South Africa’s gross domestic product and contributes to industries such as mining, agriculture and commercial forestry.[43] Our study site on the Olifants River was located at Mamba Weir (24°3’59.86” S, 31°14’33.6” E) in the KNP (Figure 1). Mamba Weir was selected as a case study site due to its location on the lower Olifants River, as one of the rivers contributing to the ecological integrity and ultimately the biodiversity of the park, and its proximity to Phalaborwa Weather Station (23°55’48.0”S 31°09’00.0”E) for recording air temperature.

Downscaled localised climate change projections for the Olifants River Catchment were developed by the Climate Systems Analysis Group (CSAG) for the United States Agency for International Development (USAID): Resilience in the Limpopo Basin Program-Olifants (RESILIM-O) programme implemented by the Association for Water and Rural Development (AWARD).[44-48] The climate model projections were performed for the Phalaborwa Weather Station and produced downscaled 25 × 25 km climate projections for 16 general circulation models (GCMs) under the Representative Concentration Pathway (RCP) 8.5 scenario which represents the ‘business as usual’ pathway for carbon emission projections in 2100 CE.[49] The climate projections produced air temperature parameters including minimum (AT_{min}) and maximum (AT_{max}) air temperatures, and average daily and average monthly temperatures were calculated.

The general regression model for river water temperature, adapted from Rivers-Moore et al.[34], based on correlations between minimum and average air temperatures and average water temperature, is shown in Equation 1:

$$WT_{max} = \left(AT_{avg} * a\right) + \left(AT_{min} * b\right) + c \qquad \text{Equation 1}$$

where WT_{max} is maximum water temperature; AT_{avg} is mean air temperature; AT_{min} is minimum air temperature; a is the mean air

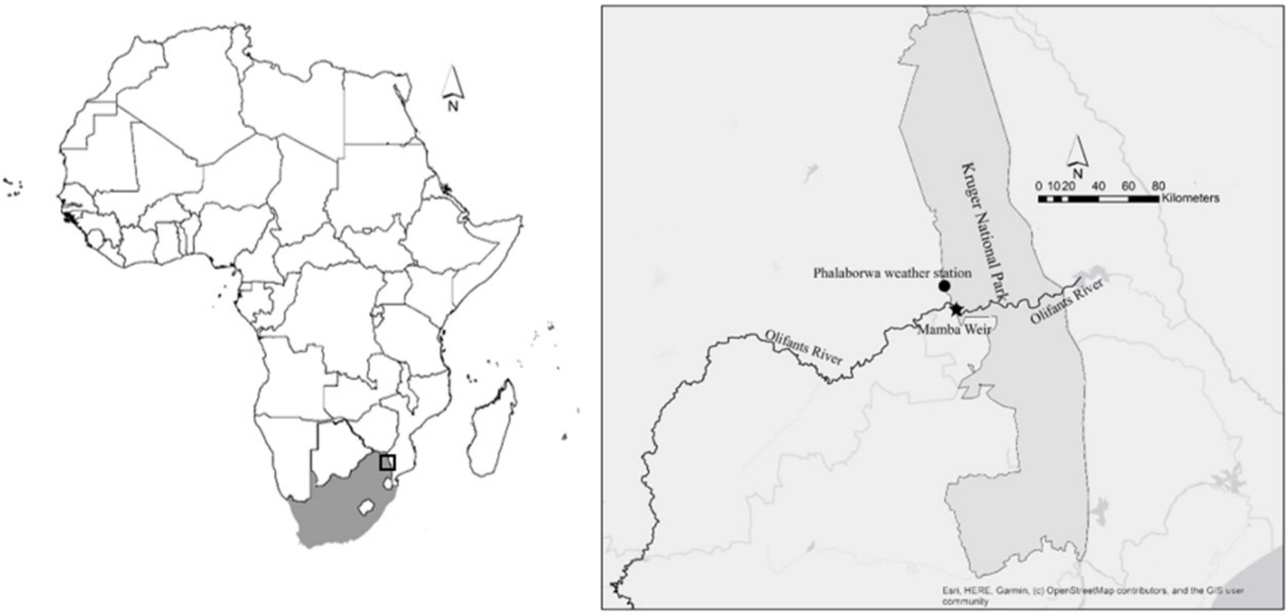

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Figure 1: Map of the study site (with an insert of Africa highlighting South Africa) showing Mamba Weir in the lower Olifants River in the Kruger National Park and Phalaborwa Weather Station, Limpopo Province, South Africa where air temperature was recorded for the study.

temperature coefficient; b is the minimum air temperature coefficient; and c is the regression constant.

The model was validated using observed water temperature data collected at Mamba Weir from August 2015 to February 2020, with continuous temperature loggers (± 0.2 °C accuracy) recording at 60-min intervals. The validation period was split into calibration (August 2015 – November 2017) and validation (December 2017 – February 2020) periods as detailed in Adlam et al.[50] Model performance was assessed using Nash–Sutcliffe efficiency (NSE) and percentage bias (PBIAS) metrics. The parameters used were $a = 0.900$, $b = 0.132$ and $c = 1.600$, and the model was validated with a NSE of 0.92 for the monthly time step and 0.78 for the daily time step and a PBIAS of –0.3% during the monthly time step and –0.17% for the daily time step.[50] The NSE values of 0.92 (monthly) and 0.78 (daily) indicate excellent to good model performance, while PBIAS values of –0.3% (monthly) and –0.17% (daily) demonstrate minimal systematic bias. The calibration and validation hydrothermographs (Figure 2) show strong agreement between observed and modelled water temperatures across both seasonal cycles and extreme events.

The validated simple regression model shown in Figure 2, in conjunction with the climate model projections downscaled by CSAG, were used to generate predictions of monthly WT_{max} and daily WT_{max} in the Olifants River from 2025 to 2100 for 16 GCMs.[49] Data quality control procedures followed the CSAG downscaling methodology. The 16 GCMs from the CMIP5 ensemble[49] were downscaled to a spatial resolution of 25 x 25 km using self-organising map-based downscaling, a statistical approximation of regional scale response based on global scale circulation and observed historical data.[45,48]

Hydrothermographs were generated to visualise seasonal and interannual variability in water temperature projections for each GCM. Box-and-whisker plots[51] were used to compare the distribution of monthly and daily water temperatures between the baseline period (2025) and the end of the century (2100). The ensemble means and range across all 16 GCMs were calculated to characterise projection uncertainty. Pairwise *t*-tests[52] were conducted for each GCM to test for statistically significant differences ($p < 0.01$) in monthly WT_{max} and in daily WT_{max} between 2025 as the beginning of the recording period and 2100 CE as the end of the projected period. Three representative GCMs were selected for detailed visualisation: inmcm4 (conservative warming), IPSL-CM5A-MR (aggressive warming) and MIROC-ESM (moderate warming), based on their position relative to the ensemble mean temperature increase.

The modelling workflow proceeded as follows: (1) downscaled daily minimum and maximum air temperatures for each GCM were obtained from CSAG for the period 2025–2100; (2) daily and monthly average air temperatures were calculated from these data; (3) Equation 1 was applied to generate daily maximum water temperature projections; (4) monthly maximum water temperature statistics (mean, maximum) were derived from daily values; and (5) ensemble statistics across all 16 GCMs were calculated for each time step.

Results

Monthly and daily summary average maximum water temperatures (WT_{avg}) for the 16 GCMs are indicated in Table 1. Generated monthly and daily hydrothermographs are shown in Figures 3 and 4, respectively, and box-and-whisker plots for monthly and daily WT_{avg} between 2025 and 2100 CE are shown in Figures 5 and 6, respectively, all showing the difference between the beginning of each recording period (2025) and end of the projected period (2100 CE). Given the same general trend shown in the derived hydrothermographs and box-and-whisker plots, only those of three GCMs that represent conservative (i.e. inmcm4), non-conservative (i.e. IPSL-CM5A-MR) and moderate (i.e. MIROC-ESM) (Table 1) GCMs are illustrated (Figures 3–6). The results show an increase in maximum monthly average water temperature (WT_{avg}) of 3–4 °C by the end of the 21st century, while the highest monthly temperature recorded in many models exceeds 33 °C (Figures 3 and 5). The daily WT_{avg} shows a similar trend, increasing ~3–4 °C by the end of the projected period, with the daily maximum water temperatures reaching up to 44 °C (Figures 4 and 6). Pairwise *t*-tests showed statistically significant differences ($p < 0.01$) between 2025 and 2100 CE for both monthly WT_{avg} (Figure 5) and daily WT_{avg} (Figure 6) data sets in all GCMs, indicating that monthly and daily WT_{avg} increases significantly over 75 years.

The monthly WT_{avg} in 2025 is 23.3–26.2 °C and increases to 25.3–30.3 °C by 2100 CE (Table 1), while the highest monthly WT_{avg} increases from 26.7–30.2 °C to 30.5–35.5 °C by 2100 CE (Table 1). The daily timescale shows

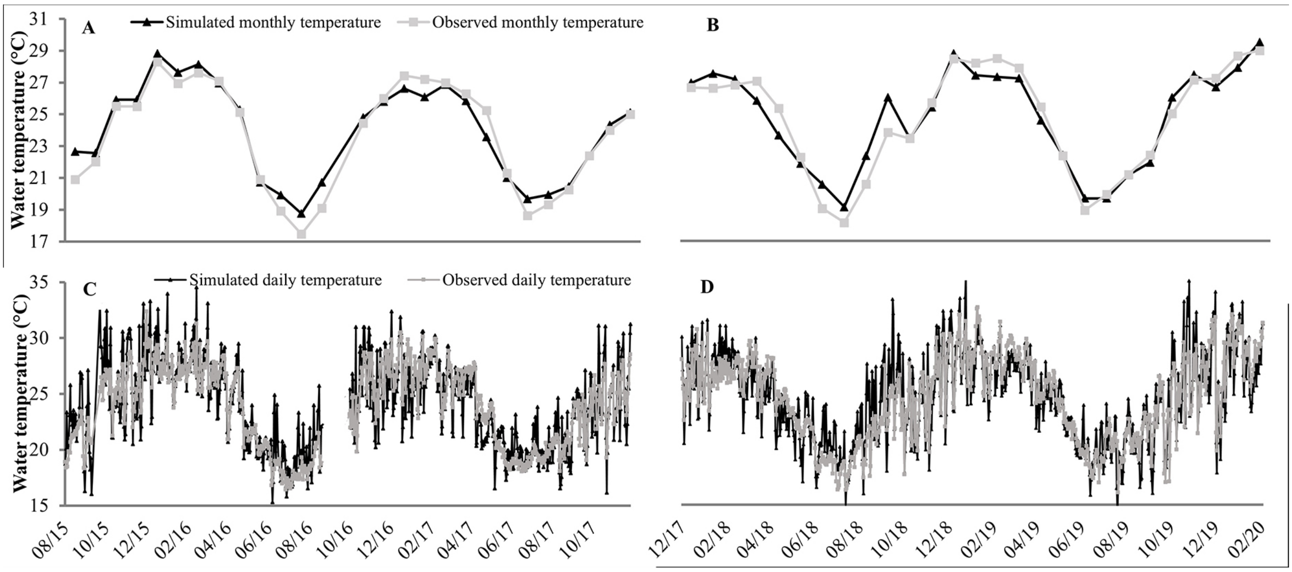

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Figure 2: Hydrothermographs of (A, B) monthly model calibration (black) and observed (grey) water temperatures, and (C, D) daily model calibration (black) and observed (grey) water temperatures, for periods August 2015 to November 2017 (A, C) and December 2017 to February 2020 (B, D) for Mamba Weir, Olifants River, South Africa. The gap in C is due to 13 days of missing observational data during September 2016. Model performance: Nash–Sutcliffe efficiency = 0.92 (monthly), 0.78 (daily); percentage bias = –0.3% (monthly), –0.17% (daily).

Table 1: A summary of average maximum water temperatures (WT_{avg}) at monthly and daily timescales for starting and ending temperatures derived from simulated time series from 2025 to 2100 CE for 16 general circulation models (GCMs) under the 'business as usual' Representative Concentration Pathway (RCP) 8.5 scenario at Mamba Weir, Kruger National Park (KNP), Limpopo Province, South Africa

GCM	Year	Monthly WT_{avg}(°C)	Highest monthly WT_{avg} (°C)	Daily WT_{avg} (°C)	Highest daily WT_{avg} (°C)
bcc-csm1-1	2025	24.5	28.9	25.6	35.6
	2100	25.3	33.3	29.2	41.1
BNU-ESM	2025	25.0	30.2	21.8	32.4
	2100	28.4	34.3	24.9	36.5
CanESM2	2025	26.2	29.9	27.3	38.4
	2100	30.1	34.5	30.9	42.7
CMCC	2025	25.4	30.4	22.3	31.9
	2100	29.9	34.3	26.6	38.1
CNRM-CM5	2025	24.7	28.4	25.7	35.7
	2100	27.3	32.7	28.1	40.3
GFDL-ESM2G	2025	24.9	28.1	26.0	36.3
	2100	28.0	32.8	28.9	42.2
GFDL-ESM2M	2025	24.7	28.6	25.8	36.0
	2100	28.7	34.6	29.6	42.5
HadGEM2-CC	2025	24.9	29.1	25.9	36.7
	2100	29.0	34.4	30.1	41.8
inmcm4	2025	23.3	26.7	24.3	34.2
	2100	26.0	30.5	26.9	38.3
IPSL-CM5A-MR	2025	25.3	30.2	26.3	36.9
	2100	30.3	35.5	31.0	44.3
IPSL-CM5B-LR	2025	24.4	29.0	25.5	36.3
	2100	27.9	33.2	28.9	41.5
MIROC5	2025	24.9	29.4	25.8	36.2
	2100	27.3	32.7	28.1	40.4
MIROC-ESM-CHEM	2025	23.8	28.5	24.9	34.9
	2100	29.3	34.0	30.2	42.0
MIROC-ESM	2025	25.1	29.5	26.1	36.8
	2100	30.2	34.4	31.1	42.6
MPI-ESM-LR	2025	24.8	28.7	25.7	36.1
	2100	28.6	33.7	29.5	41.6
MRI-CGCM3	2025	24.7	28.3	25.8	35.2
	2100	28.4	32.6	29.4	40.9
SUMMARY (Averages)	2025	24.8	29.0	25.3	35.6
	2100	28.4	33.6	29.0	41.1

that, between 2025 and 2100 CE, the WT_{avg} increases from 21.8–26.3 °C to 24.9–31.1 °C among the GCMs. The highest daily WT_{avg} increases from 31.9–38.4 °C to 36.5–44.3 °C by 2100 CE (Table 1).

The averages of the projections of the 16 GCMs show that, by 2100 CE, monthly WT_{avg} will increase from 24.8 °C to 28.4 °C (a 3.6 °C increase), while the maximum monthly WT_{avg} will rise from 29 °C to 33.6 °C

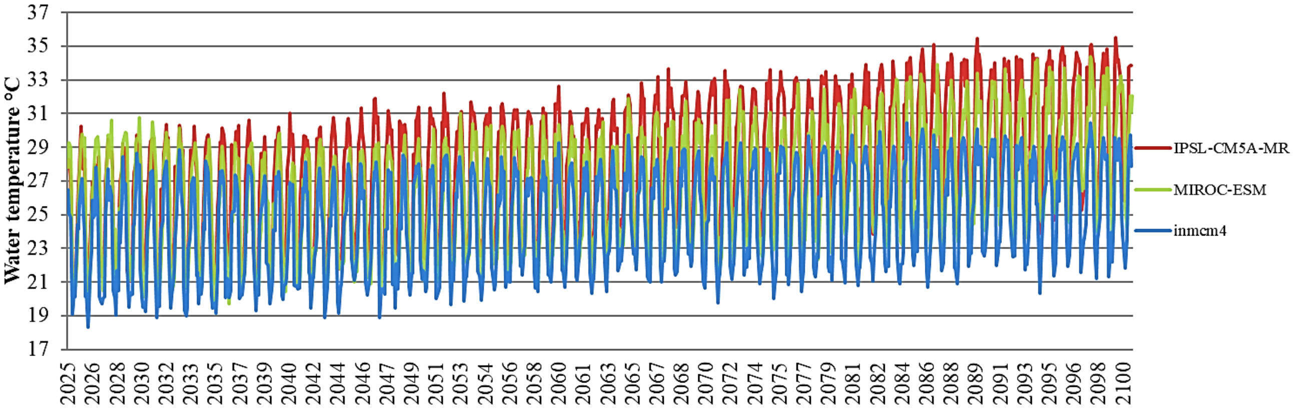

Figure 3: Hydrothermographs of monthly maximum water temperature projections from 2025 to 2100 CE under the ‘business as usual’ Representative Concentration Pathway (RCP) 8.5 scenario at Mamba Weir, Olifants River, Kruger National Park, Limpopo Province, South Africa, based on three general circulation models that represent conservative (i.e. blue = inmcm4), nonconservative (i.e. red = IPSL-CM5A-MR) and moderate (i.e. green = MIROC-ESM) models.

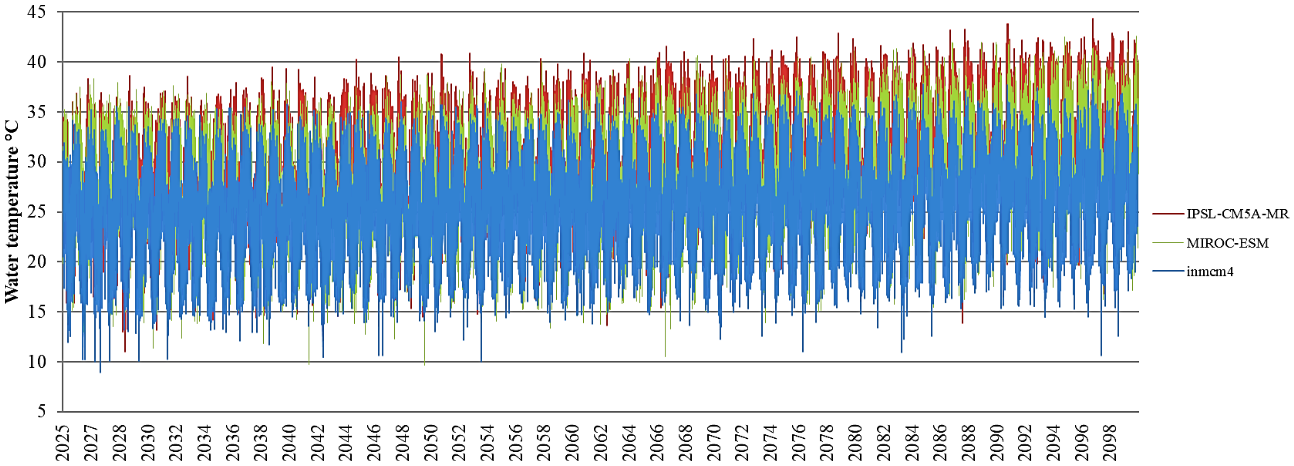

Figure 4: Hydrothermographs of daily maximum water temperature projections from 2025 to 2100 CE under the ‘business as usual’ Representative Concentration Pathway (RCP) 8.5 scenario at Mamba Weir, Olifants River, Kruger National Park (KNP), Limpopo Province, South Africa, based on three general circulation models that represent conservative (i.e. blue = inmcm4), nonconservative (i.e. red = IPSL-CM5A-MR) and moderate (i.e. green = MIROC-ESM) models.

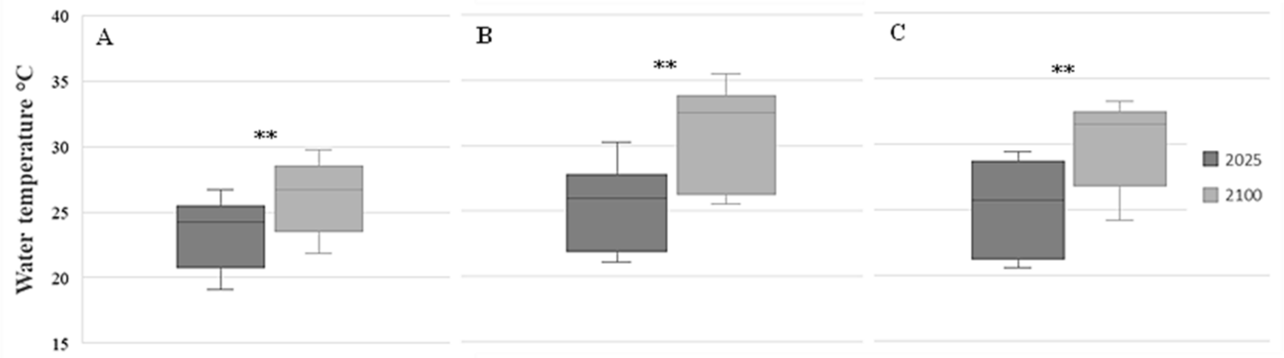

Figure 5: Box-and-whisker plots of monthly water temperature projections between 2025 (dark grey) and 2100 (light grey) under the ‘business as usual’ Representative Concentration Pathway (RCP) 8.5 scenario at Mamba Weir, Olifants River, Kruger National Park (KNP), Limpopo Province, South Africa, based on three general circulation models that represent conservative (i.e. A = inmcm4), nonconservative (i.e. B = IPSL-CM5A-MR) and moderate (i.e. C = MIROC-ESM) models. $^{**}p < 0.01$.

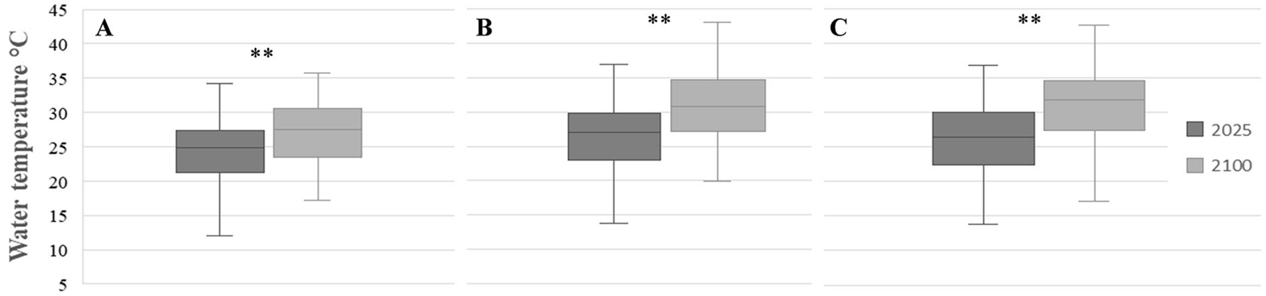

Figure 6: Box-and-whisker plots of daily water temperature projections between 2025 (dark grey) and 2100 (light grey) under the Representative Concentration Pathway (RCP) 8.5 scenario at Mamba Weir, Olifants River, Kruger National Park (KNP), Limpopo Province, South Africa, based on three general circulation models that represent conservative (i.e. A = inmcm4), nonconservative (i.e. B = IPSL-CM5A-MR) and moderate (i.e. C = MIROC-ESM) models. $^{**}p < 0.01$.

(a 4.6 °C increase). The daily timescale for air temperature from the 16 GCMs shows a similar trend, with the daily WT_{avg} showing an increase from 25.3 °C to 29.0 °C to the end of the 21st century (a 3.7 °C increase). The maximum WT_{avg} increases from 35.6 °C to 41.1 °C (a 5.5 °C increase).

Discussion

The simulations presented in this study suggest that rising air temperature as a result of climate change will translate into rising water temperature in the Olifants River, with both daily and monthly water temperatures rising by up to 5 °C by 2100 CE. Additionally, monthly water temperatures during summer will rise from 28–29 °C in 2025 to 34–35 °C by the end of the 21st century, while daily maximum temperatures may reach 42–44 °C from 36–38 °C. These results do not just indicate a large rise in water temperature but allude to the Olifants River undergoing other changes, such as increased evaporative losses and possible changes in flow regime. The river will experience changes in both thermal and physical habitats, which will have detrimental effects on the survival and breeding of freshwater species which are sensitive to disruptions in flow regime and temperature change.[29]

Our predictions are similar to those of other previous studies on the Olifants River Catchment. Singh et al.[41] used 10 GCMs to predict air temperatures between the middle of the 21st century (2046–2065) and the end of the 21st century (2081–2100) under two emission scenarios (A2 and B1). The A2 scenario describes a heterogeneous world with a rapidly growing human population, while the B1 scenario describes a convergent world with a low human population growth.[53] The B1 scenario is broadly comparable to an RCP 6.0 scenario, while the A2 scenario can be compared to the 'business as usual' RCP 8.5 scenario[54], which is the scenario that was used in the present study, and therefore its findings can be compared to those of the A2 scenario. Singh et al.[41] predicted that, by the end of the 21st century, the mean annual air temperature will increase by 4.6 °C, which translates into an increase of 13.6% in potential evapotranspiration. Olabanji et al.[38] used the Water Evaluation and Planning (WEAP) model under the RCP 8.5 scenario and found a mean temperature increase of 1 °C between 2010 and 2039, 2 °C between 2040 and 2069, and 4 °C between 2070 and 2099. The key difference between those studies and the present study is that Singh et al.[41] and Olabanji et al.[38] investigated the entire Olifants River Catchment rather than a single study site or river, and their projections were based on air temperature rather than on water temperature.

Anthropogenic climate change will not just impact water temperature, but will most likely translate into a decrease in surface water flow, most notably during the dry season, and increased water demands for mining, irrigation for agriculture and forestry, and industrial and household use.[43] Olabanji et al.[38] reported that the Olifants River Basin will have a 30% decrease in precipitation and a 17% decrease in annual average streamflow. In addition, future scenarios forecast decreased run-off[25,41], suggesting that by the end of the 21st century, unmet water demand could be as high as 80% due to decreased water flow and increased human population and its associated economic activities.[38] The Olifants River also relies on groundwater for mining, drinking and agriculture, particularly in rural communities, and to provide thermal buffering in the system.[55] However, the increase in demand for water due to a growing human population, and consequences of climate change such as changes in precipitation, land use and flow rate have altered the rate of groundwater recharge.[56] It has been predicted that, within the Olifants River Basin, groundwater recharge will decrease by 2100 CE under RCP 4.5 and RCP 8.5 scenarios[56], and this is likely to reduce thermal buffering in the region.

The Ga-Selati River within the lower Olifants catchment is also projected to have increased evaporation and decreased rainfall.[45,46] While these findings are bleak, there are examples of mitigation actions, such as those supported by the RESILIM-O project, that have been undertaken in the Olifants Basin.[44] The RESILIM-O project identified and responded to three key areas to build the resilience of the river: (1) reduction of climate vulnerability by promoting the adoption of science-based adaptation strategies in priority sub-catchments; (2) conservation and sustainable management of biodiversity in high-priority ecosystems; and 3) capacity development of stakeholders to sustainably manage water resources and biodiversity in priority sub-catchments.[44]

While the present study only addresses the effects of climate change on the abiotic factors in the Olifants River, there is a critical need to gain insights into the biotic implications of the warming of the river. For example, Dallas and Rivers-Moore[57] found that the critical thermal maxima (CT_{max}) of two macroinvertebrate families, the blackflies of the family Simuliidae (filter-feeders) and the mayflies of the family Baetidae (collector-gatherers and scrapers) were 31.6 °C and 36.7 °C, respectively. Given the results of the present study, by the end of the 21st century, the Simuliidae will experience chronic thermal stress (i.e. an impact that will eventually have severe consequences if it occurs often enough and/or at high enough levels) as they will be exposed to long periods above their CT_{max}, and therefore may undergo local extinction events. While the Baetidae could avoid chronic stress, being within the threshold of the maximum monthly temperatures, they may experience acute stress (i.e. a severe impact over a short duration) as they will be exposed to days above their CT_{max}, and this will likely result in mass die-off events. Although these are only two macroinvertebrate families that will be affected by the rising water temperatures, it is likely that there are many more species, including fishes, other vertebrates and algae that will also be either acutely or chronically affected by climate change. A similar study conducted on the Fraser River Basin in Canada found that summer temperatures during the period 2070–2099 would increase by 1.9 °C, exposing salmon to temperatures above 20 °C, which negatively affects spawning success.[58] Similarly, a study on the Douro River Basin in Portugal revealed that by 2065, a 2 °C increase is to be expected along with a decrease in annual precipitation, which will decrease the distribution of the European eel (*Anguilla anguilla*) and brown trout (*Salmo trutta fario*).[11] A study by Jones et al.[59] across the USA found that there will be a 50% reduction in thermal habitat for coldwater species such as *S. trutta*, which could translate into cumulative economic losses of between USD81 million and USD6.4 billion by 2100 CE.

Freshwater fauna are predominantly ectotherms; therefore, increases in water temperature will have profound effects on these species.[20,60] Cold-water species are vulnerable to extinction and replacement by warmer water species, leading to biological invasions.[59,61] A study in South Africa's Cape Fold Ecoregion showed that native freshwater fish species were more vulnerable than non-native species, and that climate change was more likely to increase the vulnerability of the native species.[62] Previous studies have shown that warming can cause up to 40% loss in species richness, with high extinction rates of predators and herbivores.[63] In addition, the CT_{max} of fishes will be unable to evolve fast enough to track climate change and increased water temperatures.[10] As previously mentioned, southern Africa, including the Olifants River, is predicted to be affected far greater by climate change than the global average.[24-26] The Olifants River Catchment has 37 major dams and approximately 300 minor dams and 4000 small dams, which greatly decreases connectivity and the ability for fish to track water temperature.[43] These compounding factors have severe implications for the species within these rivers as the consequences of climate change are felt. Given this, and the findings of the present study, it is clear that freshwater ecosystems are threatened at a global scale and further studies are needed on the impacts of the warming of rivers on their aquatic fauna, particularly in similarly heavily polluted and over-abstracted data-deficient freshwater systems globally.

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Data availability

The data supporting the results of this study are available upon request to the corresponding author.

Declarations

We have no competing interests to declare. We have no AI or LLM use to declare. This work is based on a PhD thesis by A.L.A. entitled 'The effects of climate change on freshwater fauna in the lower Olifants River, South Africa' (University of Pretoria; 2024).

Authors' contributions

A.L.A.: Conceptualisation, methodology, investigation, formal analysis, validation, data curation, writing – original draft, writing – review and editing, funding acquisition. C.T.C.: Writing – review and editing, supervision, funding acquisition. H.R.: Conceptualisation, methodology, investigation, data curation, writing – review and editing. S.W.: Conceptualisation, methodology, investigation, writing – review and editing, supervision. All authors read and approved the final manuscript.

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