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Peer review history for:

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HOW TO CITE:
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https://doi.org/10.17159/sajs.2026/23208/peerreview

Reviewer 1: Round 1
Date completed: 03 September 2025
Conflicts of interest: None

Recommendation: Accept / Revisions required / Resubmit for review / Resubmit elsewhere / Decline / See comments
REVIEWER: Revisions required
Does the manuscript fall within the scope of SAJS? Yes/No
REVIEWER: Yes
Is the manuscript written in a style suitable for a non-specialist and is it of wider interest than to specialists alone? Yes/No
REVIEWER: Yes
Does the manuscript contain sufficient novel and significant information to justify publication? Yes/No
REVIEWER: Yes
Do the Title and Abstract clearly and accurately reflect the content of the manuscript? Yes/No
REVIEWER: Yes
Is the research problem significant and concisely stated? Yes/No
REVIEWER: Yes
Are the methods described comprehensively? Yes/No
REVIEWER: Yes
Is the statistical treatment appropriate? Yes/No/Not applicable/Not qualified to judge
REVIEWER: Yes
Are the interpretations and conclusions justified by the research results? Yes/Partly/No
REVIEWER: Yes
Please rate the manuscript on overall contribution to the field Excellent/Good/Average/Below average/Poor
REVIEWER: Average

Please rate the manuscript on language, grammar and tone
Excellent/Good/Average/Below average/Poor

REVIEWER: Good

Is the manuscript succinct and free of repetition and redundancies?
Yes/No

REVIEWER: Yes

The number of tables in the manuscript is
Too few/Adequate/Too many/Not applicable

REVIEWER: Adequate

The number of figures in the manuscript is
Too few/Adequate/Too many/Not applicable

REVIEWER: Adequate

Are the results and discussion confined to relevance to the objective(s)?
Yes/No

REVIEWER: Yes

Is the supplementary material relevant and separated appropriately from the main document?
Yes/No/Not applicable

REVIEWER: Not applicable

Please rate the manuscript on overall quality
Excellent/Good/Average/Below average/Poor

REVIEWER: Average

Is appropriate and adequate reference made to other work in the field?
Yes/No

REVIEWER: Yes

Is it stated that ethical approval was granted by an institutional ethics committee for studies involving human subjects and non-human vertebrates?
Yes/No/Not applicable

REVIEWER: Not applicable

If accepted, would you recommend that the article receives priority publication?
Yes/No

REVIEWER: No

Are you willing to review a revision of this manuscript?
Yes/No

REVIEWER: Yes

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Yes/No

REVIEWER: Yes

Comments to the Author:
Thank you for the opportunity to review the manuscript entitled: Climate change in South African rivers: A case study on the Olifants River in the Kruger National Park. This is a succinct study which whilst geographically focused has broader regional relevance. I attach annotated review with minor comments and edits.

[See Appendix 1 for Reviewer 1's comments made directly on the manuscript]

Author response to Reviewer 1: Round 1

L90- Would be important to acknowledge the Olifants role within the larger Limpopo basin as its primary tributary - and the outcomes of your research implying broader ecosystem impacts, not only within the protected area but will have broader ecosystem outcomes

AUTHOR: Thank you for this important point. We have added text in the Methods section to better describe

the relationship between the Limpopo and Olifants rivers, and a statement at the end of the introduction emphasizing the broader impact beyond the KNP.

Changes made:

- Methods section, paragraph 1: Added "It is an important tributary of the larger Limpopo Basin that spans across four countries."
- Introduction, final paragraph: Added "Impacts in 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."

L96- Sentence not relevant when published

AUTHOR: Agreed. The sentence has been deleted

L99- Sentence a bit confusing - is the decreased runoff because of decreased rainfall (is this true?) and/or increased water use - sentence needs re-writing to clarify

AUTHOR: Thank you for identifying this lack of clarity. The sentence was intended to highlight multiple stressors that may cause habitat loss and negatively affect aquatic fauna. We have revised the sentence to better clarify these separate stressors.

Changes made:
The sentence now reads: "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..."

L165- Sentence is a bit confusing - do you mean the statistical significance was between 2025 and 2100 rather than between the two types of datasets (daily/monthly)??

Author: Thank you for pointing out this ambiguity. Yes, the statistical significance refers to the difference between 2025 and 2100 for both daily and monthly datasets separately, not between the two dataset types. We have rephrased this for clarity.

Changes made:
The text now clearly states: " 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) datasets in all GCMs …"

Reviewer 2: Round 1
Date completed: 03 September 2025
Conflicts of interest: None

Recommendation:
Accept / Revisions required / Resubmit for review / Resubmit elsewhere / Decline / See comments

REVIEWER: Revisions required

Does the manuscript fall within the scope of SAJS?
Yes/No

REVIEWER: Yes

Is the manuscript written in a style suitable for a non-specialist and is it of wider interest than to specialists alone?
Yes/No

REVIEWER: Yes

Does the manuscript contain sufficient novel and significant information to justify publication?
Yes/No

REVIEWER: No

Do the Title and Abstract clearly and accurately reflect the content of the manuscript?
Yes/No

REVIEWER: Yes

Is the research problem significant and concisely stated? Yes/No
REVIEWER: Yes
Are the methods described comprehensively? Yes/No
REVIEWER: No
Is the statistical treatment appropriate? Yes/No/Not applicable/Not qualified to judge
REVIEWER: Yes
Are the interpretations and conclusions justified by the research results? Yes/Partly/No
REVIEWER: Partly
Please rate the manuscript on overall contribution to the field Excellent/Good/Average/Below average/Poor
REVIEWER: Average
Please rate the manuscript on language, grammar and tone Excellent/Good/Average/Below average/Poor
REVIEWER: Good
Is the manuscript succinct and free of repetition and redundancies? Yes/No
REVIEWER: Yes
The number of tables in the manuscript is Too few/Adequate/Too many/Not applicable
REVIEWER: Adequate
The number of figures in the manuscript is Too few/Adequate/Too many/Not applicable
REVIEWER: Too few
Are the results and discussion confined to relevance to the objective(s)? Yes/No
REVIEWER: Yes
Is the supplementary material relevant and separated appropriately from the main document? Yes/No/Not applicable
REVIEWER: Yes
Please rate the manuscript on overall quality Excellent/Good/Average/Below average/Poor
REVIEWER: Average
Is appropriate and adequate reference made to other work in the field? Yes/No
REVIEWER: Yes
Is it stated that ethical approval was granted by an institutional ethics committee for studies involving human subjects and non-human vertebrates? Yes/No/Not applicable
REVIEWER: Not applicable
If accepted, would you recommend that the article receives priority publication? Yes/No
REVIEWER: No
Are you willing to review a revision of this manuscript? Yes/No
REVIEWER: Yes
With regard to our policy on 'Publishing peer review reports', do you give us permission to publish your anonymised peer review report alongside the authors' response, as a supplementary file to the published article? Publication is voluntary and only with permission from both yourself and the author.

Yes/No

REVIEWER: Yes

Comments to the Author:

The methodology remains insufficient to justify the results presented in the manuscript. Important details such as model validation, data quality control and statistical analysis approaches used in assessing the representativeness of downscaled and observed data are missing. The results presented are not well linked to the methodology.

[See Appendix 2 for Reviewer 2's comments made directly on the manuscript]

Author response to Reviewer 2: Round 1

L79- Name of the model and its validation?

AUTHOR: The model does not have a name. It was first described by Rivers-Moore & Lorentz, (2004) as "A simple, physically-based statistical model to simulate hourly water temperatures in a river". This has been clarified in the text by referring to it as the "general regression model for river water temperature" adapted from Rivers-Moore et al. (2008).

L106- The methodology could have benefited from a more detailed description of the model and how the observed and downscale data were actually applied in the model to generate results. A description of the model parameters, menus and setup could have strengthened the methodology further.

AUTHOR: We appreciate this important feedback and have substantially expanded the Methods section to address these concerns. Specifically, we have added:

- Model validation procedures: We have added the calibration period (August 2015 - November 2017) and validation period (December 2017 - February 2020), along with interpretation of the validation metrics (NSE and PBIAS values).
- Downscaling methodology: We have added details about the Self-Organizing Map-based downscaling (SOMD) approach used by CSAG, including spatial resolution (25 x 25 km).
- Modeling workflow: We have added a step-by-step description of how the downscaled climate data were applied to generate water temperature projections.

Reference note: The detailed validation work, model parameters and setup were previously published in Adlam *et al.* (2022). The paper has been more explicitly referenced in the expanded Methods section.

L183- Re-phrase?

AUTHOR: We have used Additionally instead

Reviewer 1: Round 2
Date completed: 10 November 2025
Conflicts of interest: None

Recommendation:
Accept / Revisions required / Resubmit for review / Resubmit elsewhere / Decline / See comments

REVIEWER: Accept

Does the manuscript fall within the scope of SAJS?
Yes/No

REVIEWER: Yes

Is the manuscript written in a style suitable for a non-specialist and is it of wider interest than to specialists alone?
Yes/No

REVIEWER: Yes

Does the manuscript contain sufficient novel and significant information to justify publication?
Yes/No

REVIEWER: Yes

Do the Title and Abstract clearly and accurately reflect the content of the manuscript? Yes/No
REVIEWER: Yes
Is the research problem significant and concisely stated? Yes/No
REVIEWER: Yes
Are the methods described comprehensively? Yes/No
REVIEWER: Yes
Is the statistical treatment appropriate? Yes/No/Not applicable/Not qualified to judge
REVIEWER: Yes
Are the interpretations and conclusions justified by the research results? Yes/Partly/No
REVIEWER: Yes
Please rate the manuscript on overall contribution to the field Excellent/Good/Average/Below average/Poor
REVIEWER: Good
Please rate the manuscript on language, grammar and tone Excellent/Good/Average/Below average/Poor
REVIEWER: Good
Is the manuscript succinct and free of repetition and redundancies? Yes/No
REVIEWER: Yes
The number of tables in the manuscript is Too few/Adequate/Too many/Not applicable
REVIEWER: Adequate
The number of figures in the manuscript is Too few/Adequate/Too many/Not applicable
REVIEWER: Adequate
Are the results and discussion confined to relevance to the objective(s)? Yes/No
REVIEWER: Yes
Is the supplementary material relevant and separated appropriately from the main document? Yes/No/Not applicable
REVIEWER: Not applicable
Please rate the manuscript on overall quality Excellent/Good/Average/Below average/Poor
REVIEWER: Good
Is appropriate and adequate reference made to other work in the field? Yes/No
REVIEWER: Yes
Is it stated that ethical approval was granted by an institutional ethics committee for studies involving human subjects and non-human vertebrates? Yes/No/Not applicable
REVIEWER: Not applicable
If accepted, would you recommend that the article receives priority publication? Yes/No
REVIEWER: No
Are you willing to review a revision of this manuscript? Yes/No
REVIEWER: No

With regard to our policy on 'Publishing peer review reports', do you give us permission to publish your anonymised peer review report alongside the authors' response, as a supplementary file to the published article? Publication is voluntary and only with permission from both yourself and the author.
Yes/No

REVIEWER: Yes

Comments to the Author:
No further comments.

Reviewer 2: Round 2
Date completed: 20 November 2025
Conflicts of interest: None

Recommendation:
Accept / Revisions required / Resubmit for review / Resubmit elsewhere / Decline / See comments

REVIEWER: Accept

Does the manuscript fall within the scope of SAJS?
Yes/No

REVIEWER: Yes

Is the manuscript written in a style suitable for a non-specialist and is it of wider interest than to specialists alone?
Yes/No

REVIEWER: No

Does the manuscript contain sufficient novel and significant information to justify publication?
Yes/No

REVIEWER: Yes

Do the Title and Abstract clearly and accurately reflect the content of the manuscript?
Yes/No

REVIEWER: Yes

Is the research problem significant and concisely stated?
Yes/No

REVIEWER: Yes

Are the methods described comprehensively?
Yes/No

REVIEWER: Yes

Is the statistical treatment appropriate?
Yes/No/Not applicable/Not qualified to judge

REVIEWER: Yes

Are the interpretations and conclusions justified by the research results?
Yes/Partly/No

REVIEWER: Yes

Please rate the manuscript on overall contribution to the field
Excellent/Good/Average/Below average/Poor

REVIEWER: Good

Please rate the manuscript on language, grammar and tone
Excellent/Good/Average/Below average/Poor

REVIEWER: Excellent

Is the manuscript succinct and free of repetition and redundancies?
Yes/No

REVIEWER: Yes

The number of tables in the manuscript is Too few/Adequate/Too many/Not applicable
REVIEWER: Adequate
The number of figures in the manuscript is Too few/Adequate/Too many/Not applicable
REVIEWER: Adequate
Are the results and discussion confined to relevance to the objective(s)? Yes/No
REVIEWER: Yes
Is the supplementary material relevant and separated appropriately from the main document? Yes/No/Not applicable
REVIEWER: Yes
Please rate the manuscript on overall quality Excellent/Good/Average/Below average/Poor
REVIEWER: Good
Is appropriate and adequate reference made to other work in the field? Yes/No
REVIEWER: Yes
Is it stated that ethical approval was granted by an institutional ethics committee for studies involving human subjects and non-human vertebrates? Yes/No/Not applicable
REVIEWER: Not applicable
If accepted, would you recommend that the article receives priority publication? Yes/No
REVIEWER: No
Are you willing to review a revision of this manuscript? Yes/No
REVIEWER: Yes
With regard to our policy on 'Publishing peer review reports', do you give us permission to publish your anonymised peer review report alongside the authors' response, as a supplementary file to the published article? Publication is voluntary and only with permission from both yourself and the author. Yes/No
REVIEWER: Yes
Comments to the Author: The manuscript presents useful insights into the potential impacts of climate change on freshwater ecosystems in a basin that is considered highly vulnerable to future climatic changes. It would have been useful to include additional sites (as opposed to the single Mamba Weir) along the Olifants River to offer a more comprehensive overview of the spatiotemporal dynamics of critical parameters such as water temperature (i.e. fluctuations between the headwaters and outlet of the basin). Further, I would caution against the use of a single weather station as a proxy for the entire Olifants River Basin as this can offer misleading statistical interpretations of the climatic dynamics in this catchment; no single weather station can be representative of an entire basin. The use of ensemble GCMs and RCP8.5 is very useful. Overall, it is a good effort that offers important insights that can be leveraged for future research.

Reviewer 3: Round 2
Date completed: 11 December 2025
Conflicts of interest: None

Recommendation: Accept / Revisions required / Resubmit for review / Resubmit elsewhere / Decline / See comments
REVIEWER: Revisions required

Does the manuscript fall within the scope of SAJS? Yes/No
REVIEWER: Yes
Is the manuscript written in a style suitable for a non-specialist and is it of wider interest than to specialists alone? Yes/No
REVIEWER: Yes
Does the manuscript contain sufficient novel and significant information to justify publication? Yes/No
REVIEWER: Yes
Do the Title and Abstract clearly and accurately reflect the content of the manuscript? Yes/No
REVIEWER: Yes
Is the research problem significant and concisely stated? Yes/No
REVIEWER: Yes
Are the methods described comprehensively? Yes/No
REVIEWER: Yes
Is the statistical treatment appropriate? Yes/No/Not applicable/Not qualified to judge
REVIEWER: Yes
Are the interpretations and conclusions justified by the research results? Yes/Partly/No
REVIEWER: Yes
Please rate the manuscript on overall contribution to the field Excellent/Good/Average/Below average/Poor
REVIEWER: Good
Please rate the manuscript on language, grammar and tone Excellent/Good/Average/Below average/Poor
REVIEWER: Good
Is the manuscript succinct and free of repetition and redundancies? Yes/No
REVIEWER: Yes
The number of tables in the manuscript is Too few/Adequate/Too many/Not applicable
REVIEWER: Adequate
The number of figures in the manuscript is Too few/Adequate/Too many/Not applicable
REVIEWER: Adequate
Are the results and discussion confined to relevance to the objective(s)? Yes/No
REVIEWER: Yes
Is the supplementary material relevant and separated appropriately from the main document? Yes/No/Not applicable
REVIEWER: Not applicable
Please rate the manuscript on overall quality Excellent/Good/Average/Below average/Poor
REVIEWER: Average

Is appropriate and adequate reference made to other work in the field?
Yes/No

REVIEWER: Yes

Is it stated that ethical approval was granted by an institutional ethics committee for studies involving human subjects and non-human vertebrates?
Yes/No/Not applicable

REVIEWER: Not applicable

If accepted, would you recommend that the article receives priority publication?
Yes/No

REVIEWER: No

Are you willing to review a revision of this manuscript?
Yes/No

REVIEWER: Yes

With regard to our policy on 'Publishing peer review reports', do you give us permission to publish your anonymised peer review report alongside the authors' response, as a supplementary file to the published article? Publication is voluntary and only with permission from both yourself and the author.
Yes/No

REVIEWER: Yes

Comments to the Author:
Nice analysis of water temperatures, and model development, under different GCMs. Minor comments in attached document to be attended to please.

[See Appendix 3 for Reviewer 3's comments made directly on the manuscript]

Author response to Reviewer 3: Round 2

L56- Meaning not clear - please rephrase especially what is meant by fragmented within terrestrial landscapes

AUTHOR: Fragmentation occurs due to anthropogenic disturbances causing a loss of connectivity in rivers/wetlands due to building of dams, roads, deforestation, mining etc.

Changes made:

- The sentence now reads "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 they cover only 0.8% of the Earth's surface area"

L212- Basin is an American term; preferred term is catchment

AUTHOR: The term Basin has been changed to Catchment

L235- To what extent? And, linked to this, to what extent is the Olifants reliant on groundwater versus quickflows?

AUTHOR: The River is less reliant on groundwater than on quickflow, however it hasn't been quantified in any study.

Changes made:

- The sentence now reads: " The Olifants River also relies on groundwater for mining, drinking, agriculture, particularly in rural communities, and to provide thermal buffering in the system."

L1241- Please indicate in Figure 1

AUTHOR: The Ga-selati is about 60km from our study site, so is not relevant to the study site map.

L252- The choice of these two families seems a little odd, as these both have relatively higher Ctmax values. Were there not other lower thermal threshold families to also consider?

At the very least, please clarify the choice of these two taxa, and indicate there relative importance/ role in river ecology e.g. filter feeders and generalists etc.

AUTHOR: These two families were only mentioned as they are the two macroinvertebrates in a study by Dallas & Rivers-Moore 2018. Simuliidae has a relatively low CTmax, while Baetidae has a moderate CTmax. They were chosen as to give an example of what may happen in terms of chronic and acute thermal stress due to climate change.

Changes made:

- feeding groups of both families included in brackets.
- And added the sentence " Loss of these families would also lead to potential loss of functional diversity and changes in food web dynamics."

L266- Worth noting that there have been South African studies of thermal impacts to fish that are worth referencing. I would imagine that the fish species relating to this study would be warm water lowveld species,. What about the cold water species upstream?

AUTHOR: Thank you for the suggestion. As this research is only on the water temperature and not yet on the species, we do not want to put too much emphasis on the biological implications. We do make a reference to cold water species "Cold water species are vulnerable to extinction and replacement by warmer water species, which also lead to biological invasions to occur."

Changes made:

- Sentence added "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."

L275- The issue of river connectivity is critical to this. Please provide a sentence or two on the extent to which the Olifants has lost connectivity.

AUTHOR: This is a good point. A sentence has been added to show the loss of connectivity.

Changes made:

- Sentence added "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."

Appendix 1: Reviewer 1's comments on manuscript (Round 1)

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

Abstract

Freshwater systems are among the most endangered ecosystems, with anthropogenic climate change causing 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. This study 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 (KNP), Limpopo Province, South Africa under the "*business as usual*" Representative Concentration Pathway (RCP) 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. Rising water temperatures in the Olifants River will ultimately change the thermal and physical landscape of the river and this forecast highlights the need for further research on the potential detrimental consequences on freshwater biota including possible ~~as~~ local extinctions.

Commented [A1]: Note these temperatures are already commonly experienced in austral spring!!

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 temperate (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 ~~of~~ on freshwater biota.

Keywords: Climate change, freshwater ecosystems, rivers, water/air temperatures, General Circulation Models (GCMs), Representative Concentration Pathway (RCP) 8.5 scenario

[**Figures are provided on the page below the references]**

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 with each other, 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 runoff which cause severe flooding during extreme weather events caused by climate change.[12,15]

Due to these cumulative impacts, along with the exponential rise in human population and demand for resources, freshwater systems are considered one of the most vulnerable ecosystems.[3,16] Freshwater systems have provided humans with services, arguably more than any other ecosystem, but because of their linear nature, any transverse or longitudinal disturbance causes cascading effects both up and downstream.[17] In the Danube Basin in Europe, a hydroelectric power plant built to supply energy to south-eastern Europe modified freshwater ecosystems to such a degree that there are changes in flow regime, habitat and disconnecting floodplains, and with an increase in energy demand due to human population growth, these are likely to be exacerbated.[18,19]

Freshwater systems are particularly vulnerable to the effects of climate change as they are fragmented and isolated within terrestrial landscapes, are exposed to anthropogenic stressors, and are also disproportionately exploited considering 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 changes in nutrient load and primary productivity, acidification, salinization, 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 given that 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, 25, 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 even 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 a specific flow regime for breeding and survival, and have very specific thermal niches, and disruptions to these parameters are 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 south-eastern Africa based on the Olifants River in the Kruger National Park KNP), Limpopo Province 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 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. ~~This study draws substantially from [Anonymised]'s [40],unpublished dissertation.~~

The KNP is already facing many challenges of water management due to pollution in its rivers from upstream and other anthropogenic disturbances.[41] The warming of these rivers, along with 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 a rise in air temperature to the end of the 21st century, both average monthly and daily water temperatures of the Olifants River will also increase, and this will ultimately have a negative effect on the aquatic fauna of this river.

Methods

Commented [A2]: Would be important to acknowledge the Olifants role within the larger Limpopo basin as its primary tributary - and the outcomes of your research implying broader ecosystem impacts, not only within the protected area but will have broader ecosystem outcomes

Commented [A3]: Sentence not relevant when published

Commented [A4]: Sentence a bit confusing - is the decreased runoff because of decreased rainfall (is this true?) and/or increased water use - sentence needs re-writing to clarify

The Olifants River Basin is ~75 000 km^2, expanding across South Africa and Mozambique.[42] The Olifants River is a perennial river that runs through the KNP which represents the largest protected area in South Africa and contributes immensely to tourism within the region, while supplying water to both South Africa and Mozambique.[41,43] It represents approximately 6% of South Africa's gross domestic product (GDP), contributing to industries such as mining, agriculture and commercial forestry.[44] The study site on the Olifants River is located at Mamba Weir (24°3'59.86" S, 31°14'33.6" E) in the KNP, Limpopo Province, South Africa as a case study site (Figure 1). Mamba Weir was selected as a case study site as it is located on the lower Olifants River in the KNP 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).[45-49] The climate model projections were performed for the Phalaborwa Weather Station and produced down-scaled 25 x 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] CSAG used an empirical down-scaling technique, the Self-Organizing Map-based downscaling, which is a statistical approximation of regional scale response based on global scale circulation and observed historical data.[46,49] 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 was adapted from Rivers-Moore *et al*.[34] based on correlations between minimum and average air temperatures, and average water temperature, as shown in Equation 1:

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

where WT_{max} = maximum water temperature; AT_{avg} = mean air temperature; AT_{min} = minimum air temperature; *a* = mean air temperature coefficient; *b* = minimum air temperature coefficient; *c* = regression constant.

The constants used were *a* = 0.900, *b* = 0.132, and *c* = 1.600, and the model validated with a Nash-Sutcliffe efficiency (NSE) of 0.92 for the monthly timestep and 0.78 for the daily timestep and had a percentage bias (PBIAS) of -0.3% during the monthly timestep and -0.17% for the

daily timestep[50] The validated simple regression model was used, in conjunction with the climate model projections produced by CSAG, to generate predictions of monthly WT_{max} and daily WT_{max} in the Olifants River from 2025 to 2100 for 16 GCMs.[50] Hydrothermographs and box and whisker plots[51] were generated using the WT_{max} projections for both daily and monthly timescales while pairwise *t*- tests[53] were used to test for statistically significant differences 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.

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 2 and 3, respectively, and box and whisker plots for monthly and daily WT_{avg} between 2025 and 2100 CE are shown in Figures 4 and 5, 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) and nonconservative (i.e., IPSL-CM5A-MR) and a moderate (i.e., MIROC-ESM) (Table 1) GCMs are illustrated (Figures 2–5). The results showed an increase in maximum monthly average water temperatures (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 2 and 4). The daily WT_{avg} show 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 3 and 5). Pairwise *t*-tests showed statistically significant differences ($P < 0.01$) in monthly WT_{avg} (Figure 4) and daily WT_{avg} (Figure 5) in all GCMs indicating that monthly and daily WT_{avg} increase between 2025 and 2100 CE.

Commented [A5]: Sentence is a bit confusing - do you mean the statistical significance was between 2025 and 2100 rather than between the two types of datasets (daily/monthly)??

The monthly WT_{avg} in 2025 is between 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 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 (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 temperature rising by up to 5° C by 2100 CE. More alarming, 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 has 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 Basin. Singh *et al*.[42] 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.[54] 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[55], 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*.[42] 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 (PE). 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*.[42] and Olabanji *et al*.[38] investigated the entire Olifants 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.[44] 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[25,42], 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 Basin also relies on

groundwater for mining, drinking, agriculture, and to provide thermal buffering in the system.[56,57] 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.[58] 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[58], and this is likely to affect thermal buffering in the region.

The Ga-Selati River within the lower Olifants catchment is also projected to have increased evaporation and decreased rainfall.[46,47] While these findings are bleak, there examples where mitigation actions ~~have~~ were already undertaken~~been taken~~ in the Olifants Basin, such as those supported by the RESILIM-O project.[45] This key project ~~run~~ conducted by AWARD (https://award.org.za/) identified and responded to three key areas to build the resilience of the river, namely: 1) Reduce climate vulnerability by promoting the adoption of science-based adaptation strategies in priority sub-catchments; 2) Conserved and sustainably managed biodiversity in high-priority ecosystems; and 3) Capacity of stakeholders developed to sustainably manage water resources and biodiversity in priority sub-catchments.[45]

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 & Rivers-Moore[59] found that the critical thermal maxima (CT_{max}) of two macroinvertebrate families, the blackflies of the family Simuliidae and the mayflies of the family Baetidae 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 may avoid the chronic stress being within the threshold of the maximum monthly temperatures, the family 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.[59] 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] More alarmingly, a study by Jones *et al.*[60] across the United States found that there will be a 50% reduction in thermal habitat for coldwater species

253 such as *S. trutta*, which will translate into cumulative economic losses of between $81 million
254 and $6.4 billion by 2100 CE.
255 Freshwater fauna are predominantly ectotherms, therefore, increases in water temperature
256 will have profound effects on these species.[20,62] Cold water species are vulnerable to extinction
257 and replacement by warmer water species, which also lead to biological invasions to occur.[61,63]
258 Previous studies have shown that warming can cause up to 40% loss in species richness, with
259 high extinction rates of predators and herbivores.[64]4 In addition, the critical thermal maxima
260 (CT_{max}) of fishes will be unable to evolve fast enough to track climate change and increased
261 water temperatures.[10] As previously mentioned, southern Africa, including the Olifants River,
262 is predicted to be affected far greater by climate change than the global average.[24-26] This
263 likely has more severe implications for the species within these rivers as the consequences of
264 climate change are felt. Given this, and the findings of the present study, it is clear that
265 freshwater ecosystems are threatened at a global scale and further studies are needed on the
266 impacts of the warming of rivers on their aquatic fauna particularly in similarly heavily polluted
267 and over-abstracted data-deficient freshwater systems globally.
268
269 **[This work is based on a Thesis/Dissertation]**

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Figures and tables

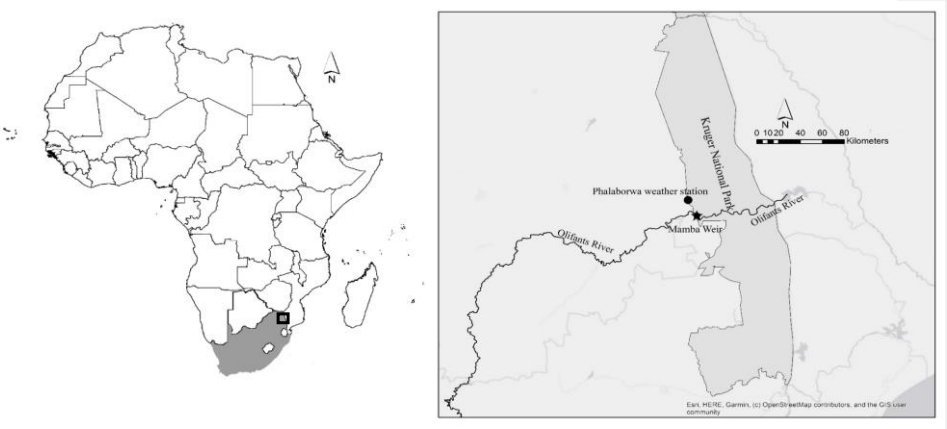

Figure 1: Map of the study site (with an insert of Africa highlighting South Africa) showing Mamba Weir in the lower Olifants River in the Kruger National Park (KNP) and Phalaborwa Weather Station, Limpopo Province, South Africa where air temperature was recorded for the study.

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.

Model	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

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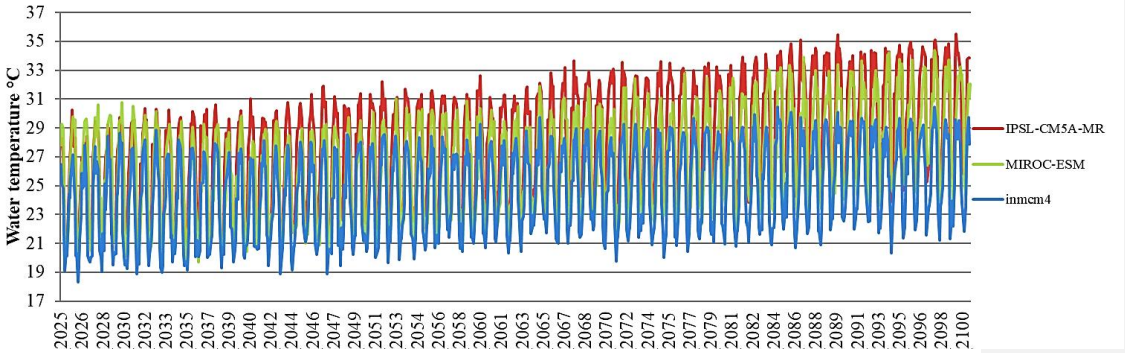

Figure 2: Hydrothermographs of monthly maximum water temperature projections from 2025 to 2100 CE under the "*business as usual*" Representative Concentration Pathway (RCP) 8.5 scenario at Mamba Weir, Olifants River, Kruger National Park (KNP), Limpopo Province, South Africa based on the following three General Circulation Models (GCMs) that represent conservative (i.e., **blue =** inmcm4) and nonconservative (i.e., **red =** IPSL-CM5A-MR) and a moderate (i.e., **green =** MIROC-ESM) GCMs.

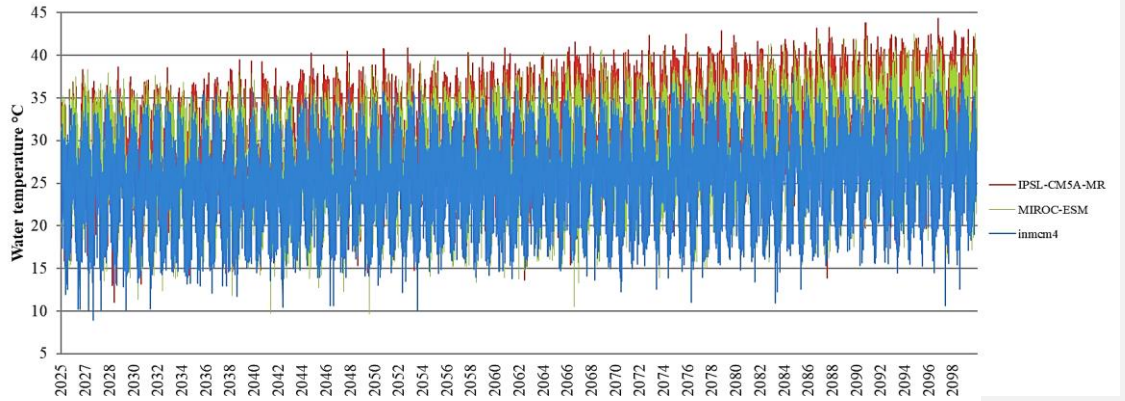

Figure 3: Hydrothermographs of daily maximum water temperature projections from 2025 to 2100 CE under the "*business as usual*" Representative Concentration Pathway (RCP) 8.5 scenario at Mamba Weir, Olifants River, Kruger National Park (KNP), Limpopo Province, South Africa based on the following three General Circulation Models (GCMs) that represent conservative (i.e., **blue =** inmcm4) and nonconservative (i.e., **red =** IPSL-CM5A-MR) and a moderate (i.e., **green =** MIROC-ESM) GCMs.

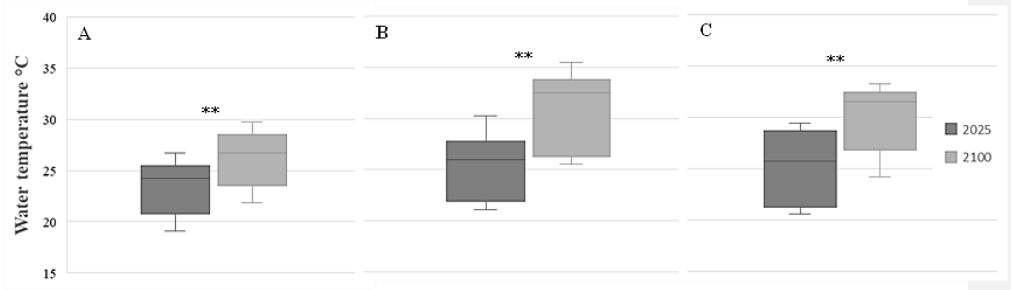

Figure 4: Box and whisker plots of monthly water temperature projections between 2025 (dark grey) and 2100 (light grey) under the "*business as usual*" Representative Concentration Pathway (RCP) 8.5 scenario at Mamba Weir, Olifants River, Kruger National Park (KNP), Limpopo Province, South Africa based the following three General Circulation Models (GCMs) that ~~that~~ represent conservative (i.e., **A =** inmcm4) and nonconservative (i.e., **B =** IPSL-CM5A-MR) and a moderate (i.e., **C =** MIROC-ESM) GCMs. Statistical significance: ** = $P < 0.01$.

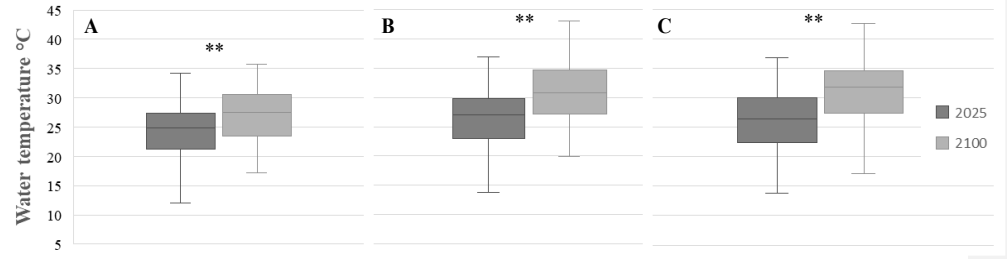

Figure 5: Box and whisker plots of daily water temperature projections between 2025 (dark grey) and 2100 (light grey) under the Representative Concentration Pathway (RCP) 8.5 scenario at Mamba Weir, Olifants River, Kruger National Park (KNP), Limpopo Province, South Africa using the following three General Circulation Models (GCMs) that represent conservative (i.e., **A =** inmcm4) and nonconservative (i.e., **B =** IPSL-CM5A-MR) and a moderate (i.e., **C =** MIROC-ESM) GCMs. Statistical significance: ** = $P < 0.01$.

Appendix 2: Reviewer 2's comments on manuscript (Round 1)

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

Abstract

Freshwater systems are among the most endangered ecosystems, with anthropogenic climate change causing 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. This study 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 (KNP), Limpopo Province, South Africa under the "*business as usual*" Representative Concentration Pathway (RCP) 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. Rising water temperatures in the Olifants River will ultimately change the thermal and physical landscape of the river and this forecast highlights the need for further research on the potential detrimental consequences on freshwater biota such as 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 temperate (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 of freshwater biota.

Keywords: Climate change, freshwater rivers, water/air temperatures, General Circulation Models (GCMs), Representative Concentration Pathway (RCP) 8.5 scenario

[**Figures are provided on the page below the references]**

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 with each other, 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~~ change infiltration rates, increasing surface runoff which cause severe flooding during extreme weather events caused by climate change.[12,15]

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

Freshwater systems are particularly vulnerable to the effects of climate change as they are fragmented and isolated within terrestrial landscapes, are exposed to anthropogenic stressors, and are also disproportionately exploited considering 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 changes in nutrient loads and primary productivity, acidification, salinization, eutrophication, flow regime, and more frequent extreme weather events such as flooding.[21–23]

Rivers in ~~the~~ southern Africa~~n subregion~~ are likely to be more affected by climate change than in other regions given that 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, 25, 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 ~~even~~ to perennial systems becoming intermittent streams, and eventually drying up.[28–30] Freshwater biota, such as fishes and macroinvertebrates, rely on ~~a~~ specific flow regimes for breeding and survival, and have very specific thermal niches, and disruptions to these parameters can be ~~are~~ 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 south-eastern Africa based on the Olifants River in the Kruger National Park (KNP), Limpopo Province 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 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. ~~This study draws substantially from [Anonymised]'s [40],unpublished dissertation~~.

The KNP is already facing many challenges of water management due to pollution in its rivers from upstream and other anthropogenic disturbances.[41] The warming of these rivers, along with 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 a rise in air temperature to the end of the 21st century, both average monthly and daily water temperatures of the Olifants River will also increase, and this will ultimately have a negative effect on the aquatic fauna of this river.

Methods

The Olifants River Basin is ~75 000 km^2, expanding across South Africa and Mozambique.[42] The Olifants River is a perennial river that runs through the KNP which represents the largest

Commented [A1]: Name of the model and its validation?

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protected area in South Africa and contributes immensely to tourism within the region, while supplying water to both South Africa and Mozambique.[41,43] It represents approximately 6% of South Africa's gross domestic product (GDP), contributing to industries such as mining, agriculture and commercial forestry.[44] The study site on the Olifants River is located at Mamba Weir (24°3'59.86" S, 31°14'33.6" E) in the KNP, Limpopo Province, South Africa as a case study site (Figure 1). Mamba Weir was selected as a case study site as it is located on the lower Olifants River in the KNP 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).[45-49] The climate model projections were performed for the Phalaborwa Weather Station and produced down-scaled 25 x 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] CSAG used an empirical down-scaling technique, the Self-Organizing Map-based downscaling, which is a statistical approximation of regional scale response based on global scale circulation and observed historical data.[46,49] 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 was adapted from Rivers-Moore *et al*.[34] based on correlations between minimum and average air temperatures, and average water temperature, as shown in Equation 1:

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

where WT_{max} = maximum water temperature; AT_{avg} = mean air temperature; AT_{min} = minimum air temperature; *a* = mean air temperature coefficient; *b* = minimum air temperature coefficient; *c* = regression constant.

The constants used were *a* = 0.900, *b* = 0.132, and *c* = 1.600, and the model validated with a Nash-Sutcliffe efficiency (NSE) of 0.92 for the monthly timestep and 0.78 for the daily timestep and had a percentage bias (PBIAS) of -0.3% during the monthly timestep and -0.17% for the daily timestep[50] The validated simple regression model was used, in conjunction with the climate model projections produced by CSAG, to generate predictions of monthly WT_{max} and

daily WT_{max} in the Olifants River from 2025 to 2100 for 16 GCMs.[50] Hydrothermographs and box and whisker plots[51] were generated using the WT_{max} projections for both daily and monthly timescales while pairwise *t*- tests[53] were used to test for statistically significant differences 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.

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 2 and 3, respectively, and box and whisker plots for monthly and daily WT_{avg} between 2025 and 2100 CE are shown in Figures 4 and 5, 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) and nonconservative (i.e., IPSL-CM5A-MR) and a moderate (i.e., MIROC-ESM) (Table 1) GCMs are illustrated (Figures 2–5). The results showed an increase in maximum monthly average water temperatures (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 2 and 4). The daily WT_{avg} show 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 3 and 5). Pairwise *t*-tests showed statistically significant differences ($P < 0.01$) in monthly WT_{avg} (Figure 4) and daily WT_{avg} (Figure 5) in all GCMs indicating that monthly and daily WT_{avg} increase between 2025 and 2100 CE.

The monthly WT_{avg} in 2025 is between 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 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 (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 temperature rising by up to 5° C by 2100 CE. More alarming, 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 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 has 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 Basin. Singh *et al*.[42] 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.[54] 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[55], 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*.[42] 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 (PE). 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*.[42] and Olabanji *et al*.[38] investigated the entire Olifants 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.[44] 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[25,42], 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 Basin also relies on

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groundwater for mining, drinking, agriculture, and to provide thermal buffering in the system.[56,57] 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.[58] 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[58], and this is likely to affect thermal buffering in the region.

The Ga-Selati River within the lower Olifants catchment is also projected to have increased evaporation and decreased rainfall.[46,47] While these findings are bleak, mitigation actions have been taken in the Olifants Basin by the RESILIM-O project.[45] This key project run by AWARD identified and responded to three key areas to build the resilience of the river, namely: 1) Reduce climate vulnerability by promoting the adoption of science-based adaptation strategies in priority sub-catchments; 2) Conserved and sustainably managed biodiversity in high-priority ecosystems; and 3) Capacity of stakeholders developed to sustainably manage water resources and biodiversity in priority sub-catchments.[45]

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 & Rivers-Moore[59] found that the critical thermal maxima (CT_{max}) of two macroinvertebrate families, the blackflies of the family Simuliidae and the mayflies of the family Baetidae 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 may undergo local extinction events. While the Baetidae may avoid the chronic stress being within the threshold of the maximum monthly temperatures, the family 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.[59] 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] More alarmingly, a study by Jones *et al.*[60] across the United States found that there will be a 50% reduction in thermal habitat for coldwater species such

as *S. trutta*, which will translate into cumulative economic losses of between $81 million and $6.4 billion by 2100 CE.

Freshwater fauna are predominantly ectotherms, therefore, increases in water temperature will have profound effects on these species.[20,62] Cold water species are vulnerable to extinction and replacement by warmer water species, which also lead to biological invasions to occur.[61,63] Previous studies have shown that warming can cause up to 40% loss in species richness, with high extinction rates of predators and herbivores.[64]4 In addition, the critical thermal maxima (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] This likely has more 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.

[This work is based on a Thesis/Dissertation]

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Figures and tables

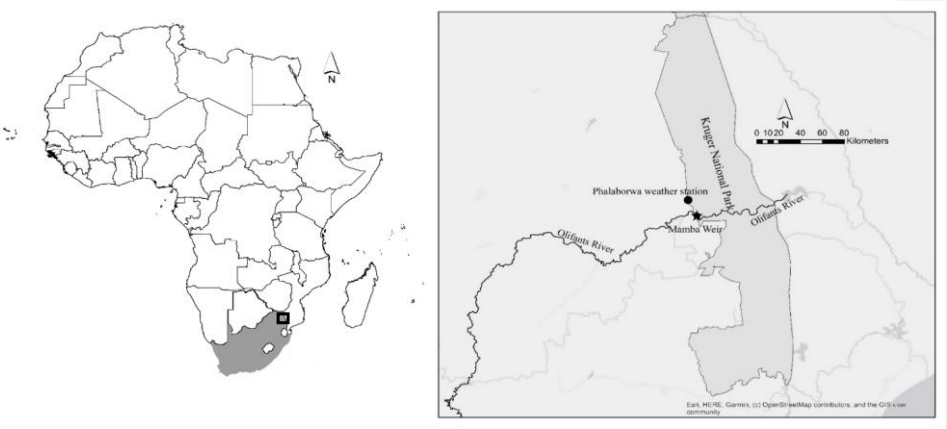

Figure 1: Map of the study site (with an insert of Africa highlighting South Africa) showing Mamba Weir in the lower Olifants River in the Kruger National Park (KNP) and Phalaborwa Weather Station, Limpopo Province, South Africa where air temperature was recorded for the study.

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.

Model	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

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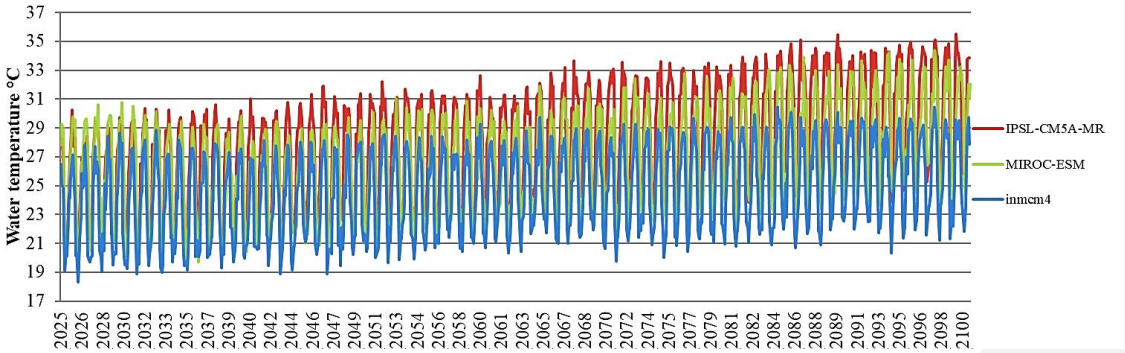

Figure 2: Hydrothermographs of monthly maximum water temperature projections from 2025 to 2100 CE under the "*business as usual*" Representative Concentration Pathway (RCP) 8.5 scenario at Mamba Weir, Olifants River, Kruger National Park (KNP), Limpopo Province, South Africa based on the following three General Circulation Models (GCMs) that represent conservative (i.e., **blue =** inmcm4) and nonconservative (i.e., **red =** IPSL-CM5A-MR) and a moderate (i.e., **green =** MIROC-ESM) GCMs.

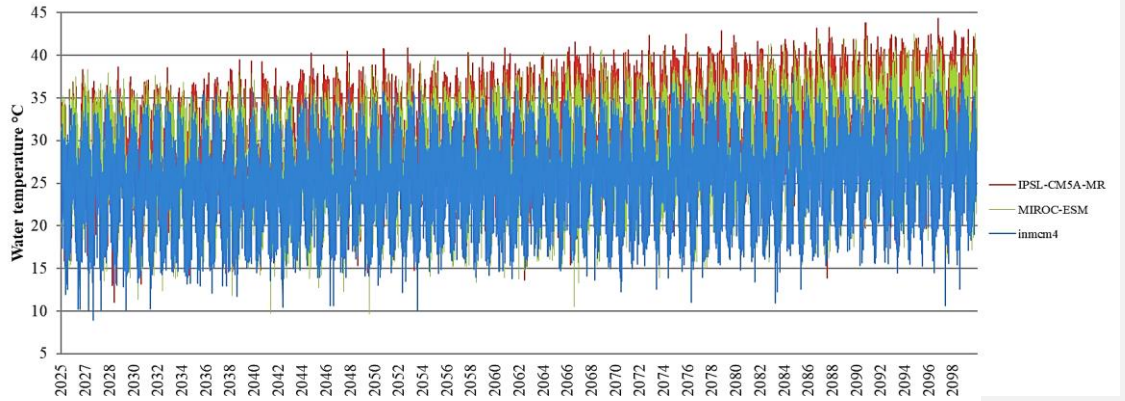

Figure 3: Hydrothermographs of daily maximum water temperature projections from 2025 to 2100 CE under the "*business as usual*" Representative Concentration Pathway (RCP) 8.5 scenario at Mamba Weir, Olifants River, Kruger National Park (KNP), Limpopo Province, South Africa based on the following three General Circulation Models (GCMs) that represent conservative (i.e., **blue =** inmcm4) and nonconservative (i.e., **red =** IPSL-CM5A-MR) and a moderate (i.e., **green =** MIROC-ESM) GCMs.

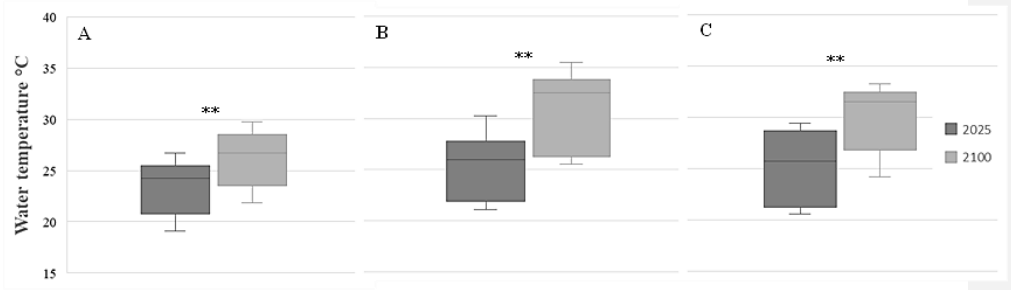

Figure 4: Box and whisker plots of monthly water temperature projections between 2025 (dark grey) and 2100 (light grey) under the "*business as usual*" Representative Concentration Pathway (RCP) 8.5 scenario at Mamba Weir, Olifants River, Kruger National Park (KNP), Limpopo Province, South Africa based the following three General Circulation Models (GCMs) that that represent conservative (i.e., **A =** inmcm4) and nonconservative (i.e., **B =** IPSL-CM5A-MR) and a moderate (i.e., **C =** MIROC-ESM) GCMs. Statistical significance: ** = $P < 0.01$.

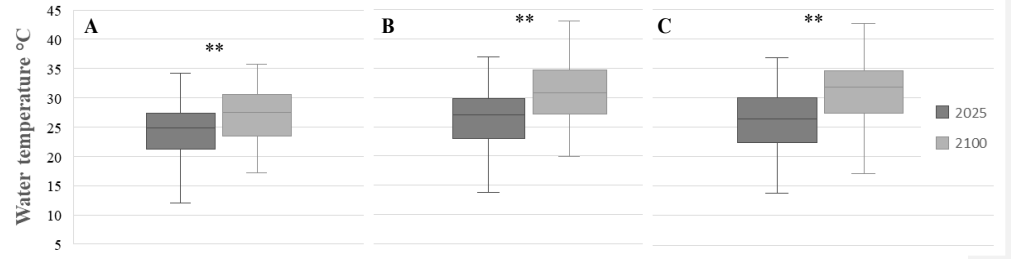

Figure 5: Box and whisker plots of daily water temperature projections between 2025 (dark grey) and 2100 (light grey) under the Representative Concentration Pathway (RCP) 8.5 scenario at Mamba Weir, Olifants River, Kruger National Park (KNP), Limpopo Province, South Africa using the following three General Circulation Models (GCMs) that represent conservative (i.e., **A =** inmcm4) and nonconservative (i.e., **B =** IPSL-CM5A-MR) and a moderate (i.e., **C =** MIROC-ESM) GCMs. Statistical significance: ** = $P < 0.01$.

Appendix 3: Reviewer 3's comments on manuscript (Round 2)

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

Abstract

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. This study 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 (KNP), Limpopo Province, South Africa, under the "*business as usual*" Representative Concentration Pathway (RCP) 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 other 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 temperate (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.

Keywords: Climate change, freshwater ecosystems, rivers, water/air temperatures, General Circulation Models (GCMs), Representative Concentration Pathway (RCP) 8.5 scenario

[**Figures are provided on the page below the references]**

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 with each other, 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 runoff which cause severe flooding during extreme weather events caused by climate change.[12,15]

Due to these cumulative impacts, along with the rise in human population and 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 up and downstream.[17] In the Danube Basin in Europe, for instance, a hydroelectric power plant built to supply energy to south-eastern Europe modified freshwater ecosystems to such a degree that it resulted in changes in flow regime, habitat and disconnecting floodplains, and with an increase in energy demand due to human population growth, these are likely to be exacerbated.[18,19]

Freshwater systems are particularly vulnerable to the effects of climate change as they are fragmented and isolated within terrestrial landscapes, are exposed to anthropogenic stressors, and are also disproportionately exploited considering 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 changes in nutrient load and primary productivity, acidification, salinization, 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 given that 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, 25, 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

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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 south-eastern Africa based on the Olifants River in the Kruger National Park (KNP), Limpopo Province 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 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 a rise in air temperature to the end of the 21st century, both average monthly and daily water temperatures of the Olifants River will also increase, and this will ultimately have a negative effect on the aquatic fauna of this river. Impacts in 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~~Basin~~ is ~75 000 km^2, 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~~immensely~~ 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 (GDP), contributing to industries such as mining, agriculture and commercial forestry.[43] The study site on the Olifants River is located at Mamba Weir (24°3'59.86" S, 31°14'33.6" E) in the KNP as a case study site (Figure 1). Mamba Weir was selected as a case study site as it is located 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 down-scaled 25 x 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 was 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:

$$WT_{max} = (AT_{avg} * a) + (AT_{min} * b) + c \quad [Equation\ 1]$$

where WT_{max} = maximum water temperature; AT_{avg} = mean air temperature; AT_{min} = minimum air temperature; *a* = mean air temperature coefficient; *b* = minimum air temperature coefficient; *c* = 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-minute 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.* (2022).[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 validated with a NSE of 0.92 for the monthly timestep and 0.78 for the daily timestep and a PBIAS of -0.3% during the monthly timestep and -0.17% for the daily timestep.[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-Organizing Map-based downscaling (SOMD), a statistical approximation of regional scale response based on global scale circulation and observed historical data.[45,48]

Hydro-thermographs 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 end of century (2100). The ensemble means and range across all 16 GCMs were calculated to characterize 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 visualization: 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 hydro-thermographs 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 hydro-thermographs and box and whisker plots, only those of three GCMs that represent conservative (i.e., inmcm4), ~~and~~ nonconservative (i.e., IPSL-CM5A-MR) and ~~a~~ moderate (i.e., MIROC-ESM) (Table 1) GCMs are illustrated (Figures 3–6). The results showed an increase in maximum monthly average water temperatures (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} show 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) datasets in all GCMs indicating that monthly and daily WT_{avg} increases significantly over 75 years.

The monthly WT_{avg} in 2025 is between 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 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 (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 temperature 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 has 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~~Basin~~. 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 (PE). 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

Commented [A2]: Basin is an American term; preferred term is catchment

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 ~~Basin also~~ relies on groundwater for mining, drinking, agriculture, and to provide thermal buffering in the system.[55,56] 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.[57] 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[57], and this is likely to reduce~~affect~~ 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, examples where mitigation actions such as those supported by the RESILIM-O project have been undertaken in the Olifants Basin.[44] This ~~key~~ project ~~conducted by AWARD~~ identified and responded to three key areas to build the resilience of the river, namely: 1) Reduce climate vulnerability by promoting the adoption of science-based adaptation strategies in priority sub-catchments; 2) Conserved and sustainably managed biodiversity in high-priority ecosystems; and 3) Capacity of stakeholders developed 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 & Rivers-Moore[58] found that the critical thermal maxima (CT_{max}) of two macroinvertebrate families, the blackflies of the family Simuliidae and the mayflies of the family Baetidae 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 may avoid the chronic stress being within the threshold of the maximum monthly temperatures, the family 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

Commented [A3]: To what extent? And, linked to this, to what extent is the Olifants reliant on groundwater versus quickflows?

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Commented [A5]: The choice of these two families seems a little odd, as these both have relatively higher Ctmax values. Were there not other lower thermal threshold families to also consider?
At the very least, please clarify the choice of these two taxa, and indicate there relative importance/ role in river ecology e.g. filter feeders and generalists etc.

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.[59] 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*.[60] across the United States found that there will be a 50% reduction in thermal habitat for coldwater species such as *S. trutta*, which could~~will~~ translate into cumulative economic losses of between $81 million and $6.4 billion by 2100 CE.

Freshwater fauna are predominantly ectotherms, therefore, increases in water temperature will have profound effects on these species.[20,61] Cold water species are vulnerable to extinction and replacement by warmer water species, which also lead to biological invasions to occur.[60,62] 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 critical thermal maxima (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] This likely has more 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~~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.

[This work is based on a Thesis/Dissertation]

Commented [A6]: Worth noting that there have been South African studies of thermal impacts to fish that are worth referencing. I would imagine that the fish species relating to this study would be warm water lowveld species,. What about the cold water species upstream?

Commented [A7]: The issue of river connectivity is critical to this. Please provide a sentence or two on the extent to which the Olifants has lost connectivity.

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Figures and tables

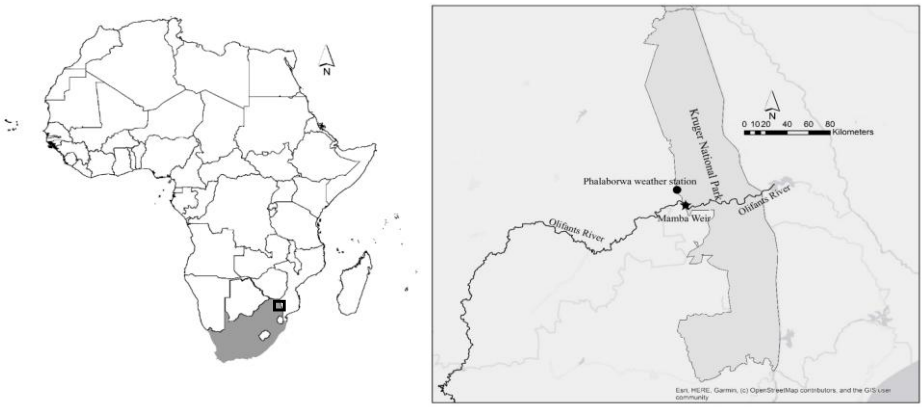

Figure 1: Map of the study site (with an insert of Africa highlighting South Africa) showing Mamba Weir in the lower Olifants River in the Kruger National Park (KNP) and Phalaborwa Weather Station, Limpopo Province, South Africa where air temperature was recorded for the study.

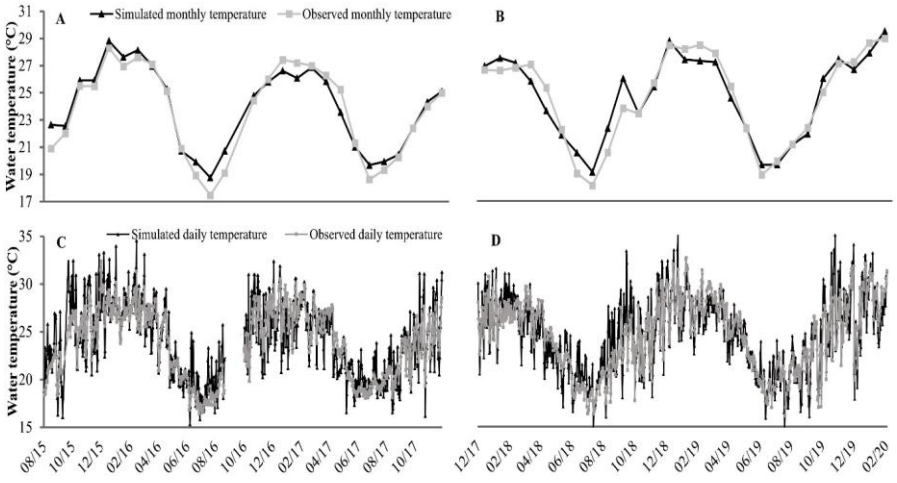

Figure 2: Hydrothermographs of: **(A, B)** - Monthly model calibration (black) and observed (grey) water temperatures, and **(C, D)** - daily model calibration (black) and observed (grey) water temperatures, for periods August 2015 to November 2017 **(A, C)** and December 2017 to February 2020 **(B, 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: NSE = 0.92 (monthly), 0.78 (daily); PBIAS = -0.3% (monthly), -0.17% (daily). Adapted from Adlam *et al*. (2022).

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.

Model	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

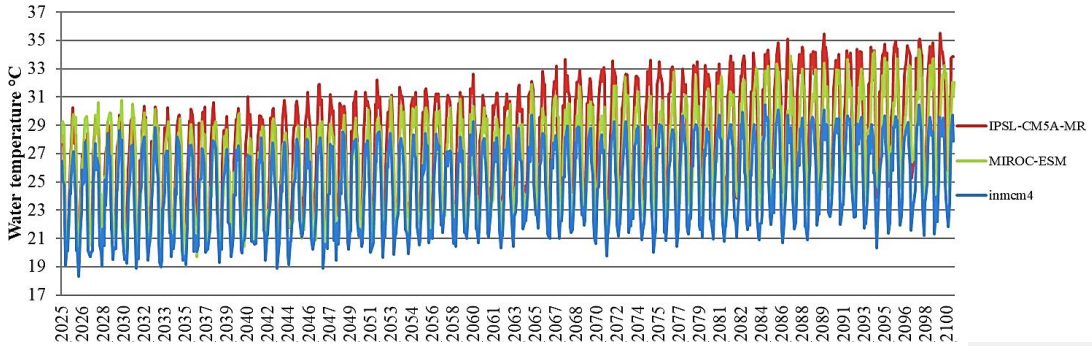

Figure 3: Hydrothermographs of monthly maximum water temperature projections from 2025 to 2100 CE under the "*business as usual*" Representative Concentration Pathway (RCP) 8.5 scenario at Mamba Weir, Olifants River, Kruger National Park (KNP), Limpopo Province, South Africa based on ~~the following~~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

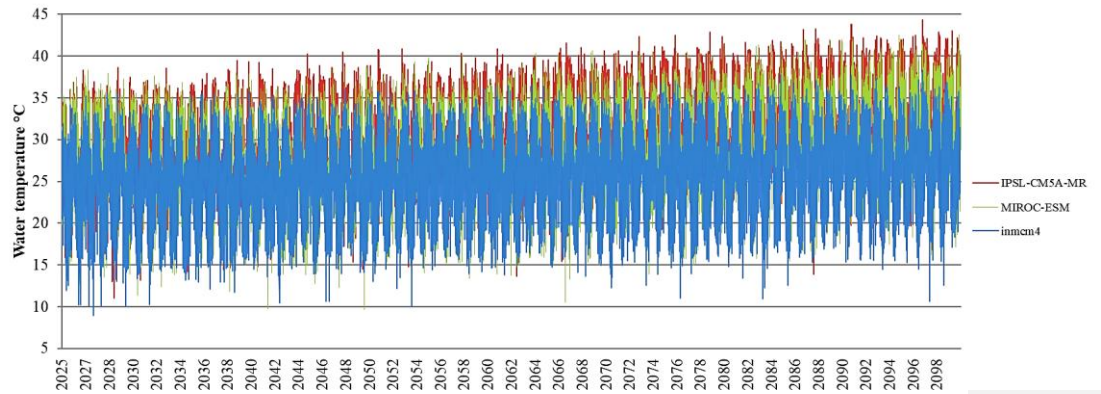

Figure 4: Hydrothermographs of daily maximum water temperature projections from 2025 to 2100 CE under the "*business as usual*" Representative Concentration Pathway (RCP) 8.5 scenario at Mamba Weir, Olifants River, Kruger National Park (KNP), Limpopo Province, South Africa based on ~~the following~~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

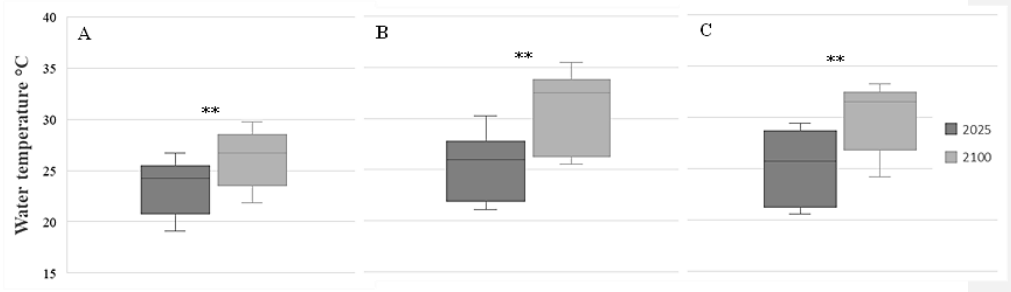

Figure 5: Box and whisker plots of monthly water temperature projections between 2025 (dark grey) and 2100 (light grey) under the "*business as usual*" Representative Concentration Pathway (RCP) 8.5 scenario at Mamba Weir, Olifants River, Kruger National Park (KNP), Limpopo Province, South Africa based on ~~the following~~ three General Circulation Models (GCMs) that represent conservative (i.e., **A =** inmcm4), ~~and~~ nonconservative (i.e., **B =** IPSL-CM5A-MR) and a moderate (i.e., **C =** MIROC-ESM) GCMs. Statistical significance: ** = $P < 0.01$.

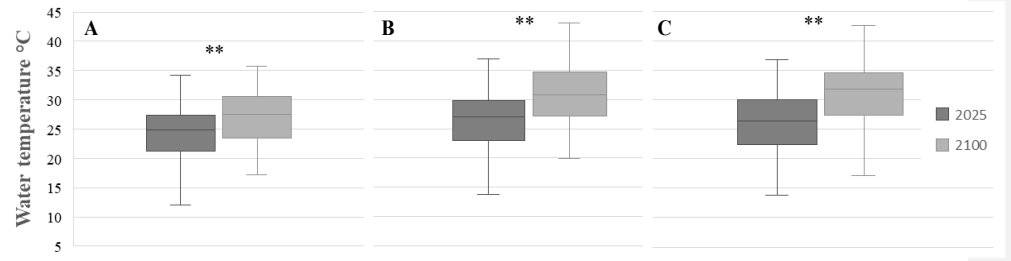

Figure 6: Box and whisker plots of daily water temperature projections between 2025 (dark grey) and 2100 (light grey) under the Representative Concentration Pathway (RCP) 8.5 scenario at Mamba Weir, Olifants River, Kruger National Park (KNP), Limpopo Province, South Africa using ~~the following~~ three General Circulation Models (GCMs) that represent conservative (i.e., **A =** inmcm4), ~~and~~ nonconservative (i.e., **B =** IPSL-CM5A-MR) and ~~a~~ moderate (i.e., **C =** MIROC-ESM) GCMs. Statistical significance: ** = $P < 0.01$.