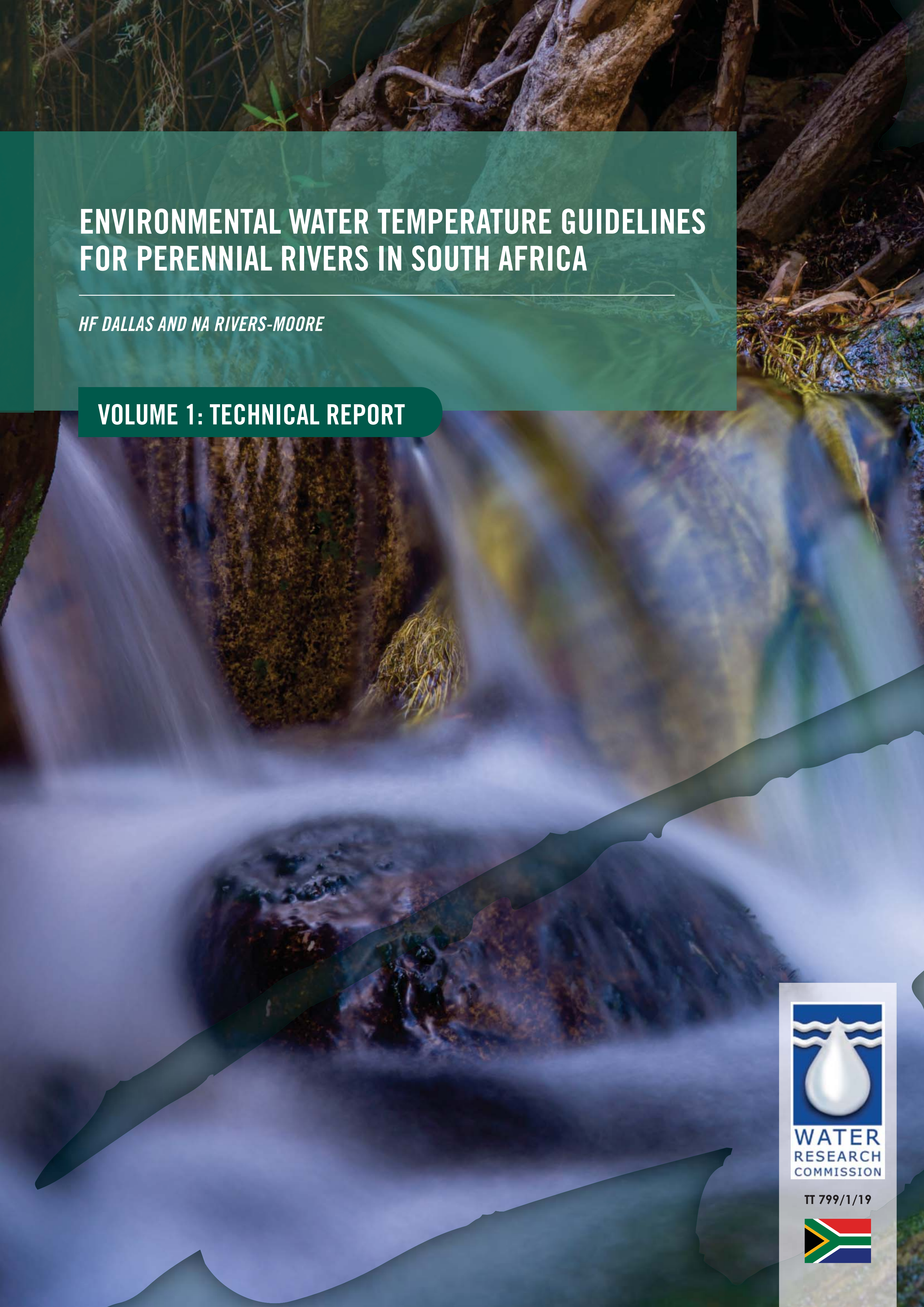

ENVIRONMENTAL WATER TEMPERATURE GUIDELINES FOR PERENNIAL RIVERS IN SOUTH AFRICA

HF DALLAS AND NA RIVERS-MOORE

VOLUME 1: TECHNICAL REPORT

WATER RESEARCH COMMISSION

TT 799/1/19

Environmental water temperature guidelines for perennial rivers in South Africa

Volume 1: Technical Report

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WATER RESEARCH COMMISSION
by

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Freshwater Research Centre

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The companion publication to this report is:
Dallas HF and Rivers-Moore NA. 2019. Environmental water temperature guidelines for perennial rivers in South Africa. Volume 2: A technical manual for setting water temperature targets. Water Research Commission Report no. TT 799/2/19, Water Research Commission, Pretoria.

Volume 1 provides the technical background to the project, including an overview of water temperature, thermal impacts and the effect of thermal changes on river organisms. It outlines the engagement with water resource practitioners during the project, and provides a summary of the protocol for establishing environmental temperature guidelines for perennial rivers in South Africa, demonstrated with three case studies. It includes, as a resource, a list of publications related to this research.

Volume 2 is the technical manual for setting water temperature targets for perennial rivers in South Africa. The manual serves as a road map for water resource practitioners needing to incorporate water temperature into Resource Directed Measures, including ecological Reserves and Resource Quality Objectives, and Source Directed Controls. It speaks directly to several tools, packaged into a toolbox, developed for establishing environmental water temperature guidelines.

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EXECUTIVE SUMMARY

1.1 Research background and motivation

In 2015, all 193 member States of the United Nations general assembly unanimously agreed to commit to *Transforming our world: the 2030 Agenda for Sustainable Development*. The 2030 Agenda is a plan of action for people, the planet and prosperity. Member states resolved to "*end poverty in all its forms"*, to take bold and transformative steps to *"shift the world on to a sustainable and resilient path"* and to ensure that *"no one will be left behind*" (United Nations 2018). The 2030 Agenda established 17 Sustainable Development Goals (SDGs), including SDG 6 (Ensure availability and sustainable management of water and sanitation for all), SDG 13 (Take urgent action to combat climate change and its impacts) and SDG 15 (Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification and halt and reverse land degradation, and halt biodiversity loss). SDG 6 includes clause 6.6 - restoring water-related ecosystems, which underpins other SDGs, particularly those relating to food and energy production, biodiversity, and land and sea ecosystems. Member states recognised that protecting and restoring water-related ecosystems cannot be achieved without progress on these other goals and vice versa. They further recognised that monitoring at both the ecosystem level and at the catchment scale is important, with local-scale monitoring providing evidence for practical action, while larger catchment-scale monitoring provides an overall perspective. A common thread throughout the SDG dialogue is that effective water resource management needs more and better data. Data underpin good water governance and the time to act on SDG 6 is now!

Knowledge generated during this project on water temperature characteristics of rivers, thermal impacts and biotic responses to changes in water temperature; and the protocol and tools developed for managing river ecosystems; contributes to each of these SDGs, in particular to water-related ecosystem management, climate resilience and freshwater biodiversity. Water temperature is a key component of aquatic ecosystems and understanding the role of temperature in these systems and the ecological consequences of changes in water temperature, is critically important. Human activities, including catchment transformation, have cumulatively altered natural thermal regimes, with impacts and occurrence of extreme events amplified and exacerbated by global climate change. These extremes in temperature will affect many species, especially freshwater species, as they are more restricted in their movement and the smaller water bodies they inhabit heat up more rapidly.

Southern Africa is a 'critical region' of water stress and existing anthropogenic stresses on freshwater ecosystems are substantial. Freshwater ecosystems are also amongst the most vulnerable in the world with respect to global climate change, with climate driven by radiation from the sun, by heat and by water, and there is thus an urgency to manage these systems appropriately. Climate change has a significant impact on freshwater systems and their management since water is a key resource and is the critical way that climate change impacts are felt (droughts, floods, storms, melting glaciers and sea-level rise). Good water management helps with adaptation to climate change. Within South Africa's National Water Act, water temperature is a bridging variable between the water quality and water quantity aspects of the ecological reserve. Globally, the International Union for Conservation of Nature advocates thinking of water as a connector, not a sector. Like climate change itself, water is a cross-cutting sector that touches on sustainability and biodiversity, as well as a range of non-environmental sectors including power generation, industry, agriculture, and urban development.

Nature has a strong role to play in climate change adaptation, especially water storage and flood control, and promotion of nature-based solutions (NBSs) will ultimately help to reduce costs and increase cost-effectiveness of engineered infrastructure and increase the co-benefits including biodiversity conservation. NBSs use or mimic natural processes to increase water availability (e.g. soil moisture retention and groundwater recharge), improve water quality (e.g. natural and constructed wetlands and riparian buffer strips), and reduce water-related risks by restoring flood plains and constructing decentralized water retention systems, such as green roofs (United Nations 2018). From a climate change perspective, climate resilience can be strengthened through healthy ecosystem services that rely on well-functioning river catchments.

1.2 Research objectives

The overall objective of this project was to translate knowledge generated over ten years of thermal research in South Africa into a protocol for water resource practitioners to incorporate water temperature into Resource Directed Measures, including ecological Reserves and Resource Quality Objectives, and Source Directed Controls for perennial rivers in South Africa. This project thus aimed to bridge the gap between science/research and management/implementation, by taking the body of research on water temperature and packaging it in ways that best serves the end-users.

The specific aims of this project were as follows:

- To identify requirements of river managers and practitioners for incorporating water temperature into the ecological Reserve.
- To develop a protocol for collection and/or derivation of water temperature time series data.
- To develop tools for setting water temperature targets for perennial rivers in South Africa.
- To produce a manual for setting water temperature targets for perennial rivers in South Africa.
- To disseminate knowledge on the protocol, tools and guidelines through workshops and discussions.

1.3 Summary of main results and conclusions

1.3.1 Routine monitoring of water temperature in South African rivers

Following extensive consultation with water resource practitioners via questionnaires, workshops and individually, there was unanimous recognition that water temperature urgently needs to be routinely monitored in South African rivers. This needs to be done on an hourly basis to enable long-term trends to be established, as well at site-specific impacts, where appropriate. The focus needs to be on selecting a set of strategic national sites, aligned with the outcomes of the National Water Resources Monitoring Network Project's final set of monitoring sites (Department of Water and Sanitation 2017), and potentially linked to existing River Ecostatus Monitoring Programme sites and the Ecological Water Requirements sites. A conservative approach was advocated, by strategically selecting sites in areas where data and capacity already exist. The suggestion was made that a number of sites in selected Western Cape rivers be identified as a starting point. There was also recognition of the potential strength in cooperation between institutions and organisations to establish long-term water temperature monitoring sites. The Protected Area Networks and conservation organisations (including SANParks, CapeNature, etc) should be considered as a spatial framework within which water temperature is routinely monitored. This would be especially valuable for determination of thermal reference envelopes and would serve as a benchmark for monitoring the long-term effect of global climate change on river systems. Strategic Water Source Areas (WWF 2013), which are source areas often regarded as natural "water factories" since they support growth and develop needs that are often far away, should also be considered.

1.3.2 Key thermal impacts and their prevalence in South African rivers

Key thermal impacts and their prevalence in South African rivers have been tabulated, and management and mitigation options outlined. These impacts include both point [heated water from power plants; altered (heated or cooled) effluent from industries; heated effluent from mines, including mine dewatering; treated wastewater from waste water treatment works and water treatment works; flow modification (e.g. river regulation and impoundments); surface water abstraction; flow augmentation (e.g. inter-basin water transfer); groundwater abstraction; agricultural/irrigation return flows], and non-point (land-use change – urban runoff/catchment hardening; modification of riparian vegetation; modification of channel morphology; and global climate change) source impacts. This information will assist water resource practitioners to assess the risk of thermal impacts and formulate management and mitigation options and plans.

1.3.3 Effects of thermal changes on river organisms

Biological effects of changes in water temperature (and flow) on river organisms are described and categorised as physiological, metabolic, phenological, reproductive, behavioural or ecological. Effects range from individual- to population-level modifications such as alteration of individual life history patterns, increases in the number and spread of invasive and pest species (such as blackfly), increase in waterborne and vector-borne diseases (cholera, malaria, etc), extinction of vulnerable species, shifts in species distribution and range, and changes in communities and aquatic biodiversity. This information will assist water resource practitioners to understand the likely ecological consequences of thermal stress, at multiple scales. For some effects, societal costs of altered thermal regimes need to be factored into the cost-benefit equations of catchment changes, which typically manifest in economic sectors and/or communities that don't directly reap the benefits. Examples of this include outbreaks of water-borne diseases (cholera etc) and outbreaks of pest species such as blackfly downstream of impoundments.

1.3.4 A protocol for establishing environmental water temperature guidelines and setting water temperature targets for perennial rivers in South Africa

To enable water resource practitioners to set water temperature targets for perennial rivers in South Africa, a technical manual has been produced that serves as a road map for practitioners needing to incorporate water temperature into Resource Directed Measures, including ecological Reserves and Resource Quality Objectives, and Source Directed Controls. It speaks directly to several tools, packaged into a toolbox, developed for establishing environmental water temperature guidelines. The protocol was informed by the end-user requirements workshops, in particular the need for a screening process, which has been integrated into the protocol. The protocol comprises two processes that need to be followed for establishing environmental water temperature guidelines, namely a Screening Process and an Evaluation Process.

The **Screening Process** allows water resource practitioners to evaluate whether or not water temperature should be considered at a particular site, be it for setting an environmental water temperature guideline or evaluating the potential effect of a thermal impact. Three key questions are asked: 1) How resilient is the site, reach or river to changes in water temperature? 2) Are there other hydrological, physico-chemical (water quality) or habitat considerations that could magnify or diminish thermal impacts? and 3) How sensitive are the river organisms? The final stage of the screening process is an assessment of thermal stress in terms of risk using a thermal risk assessment matrix that enables practitioners to assess the likely risk of thermal impact in the case of existing stressors and/or proposed stressors. This informs whether water temperature needs to be further examined at a site, in which case the water resource practitioner continues on with the Evaluation Process.

The **Evaluation Process** is sub-divided into two components: 1) establishing Reference Indicators of Thermal Alteration (thermal metrics) and a Reference Thermograph, and 2) evaluating deviation of water temperature monitoring data from Reference thermal metrics and a Reference Thermograph, including the determination of the Ecological Category (A to F). This allows water resource practitioners to set thermal targets for specific reference sites, reaches or rivers, using either logged water temperature data or modelled water temperature data, and to evaluate changes in water temperature at comparable monitoring sites, reaches or rivers.

1.3.5 A protocol for collecting water temperature data

A protocol for collecting water temperature data has been produced which includes the choice of the logger, housing construction, and tips for the installation and positioning of water temperature loggers in a river channel.

1.3.6 A spatial framework

A spatial framework which classifies each quinary catchment into "Upland" or "Lowland" geomorphological zones has been developed for South Africa. This serves as the framework within which air-water temperature models are selected, and within which reference thermographs could be defined where data become available.

1.3.7 A national map of system resilience and associated radar plots

A database of variables likely to indicate system (river) resilience to thermal stress has been developed for all quinary catchments in South Africa. The resilience of a river is likely to be affected by variables such as stream order, groundwater depth, flow predictability, water yield (i.e. precipitation minus evaporation) and catchment transformation. The resilience ratings (from 0 to 1) for each variable have been summed to generate a Total Resilience Score for each quinary and used to generate a map of system resilience to thermal stress for South Africa. Radar plots show the relative importance of the five variables potentially affecting system resilience.

1.3.8 A national map of air temperature - water temperature model accuracy and associated radar plots

A number of air temperature – water temperature models have been developed for different regions of South Africa. Given that the reliability and accuracy of these models varies, a database of variables likely to assist with evaluating model accuracy has been developed for all quinary catchments in South Africa. Model accuracy is affected by stream order, groundwater depth, flow predictability, water yield and channel incision. The accuracy ratings (from 0 to 1) for each variable have been summed to generate a Model Accuracy Score for each quinary and used to generate a map of model accuracy for South Africa. Radar plots show the relative importance of five variables potentially affecting model accuracy.

1.3.9 Thermal Sensitivity Index

A prototype Thermal Sensitivity Index based on aquatic macroinvertebrates has been developed, whereby each taxon is assigned a Thermal Sensitivity Weighting based on a combination of an estimate of thermophily and thermal limits determined experimentally. These Thermal Sensitivity Weightings have been applied to most taxa in the South African Scoring System (SASS) making it relatively easy for a water resource practitioner to determine if highly and/or moderately thermally sensitive taxa are present at a site. Further validation of the efficacy of this prototype is however required, although the grouping of taxa based on thermal sensitivity may be used independently of the Thermal Sensitivity Index.

1.4 Research achievements and outcomes

1.4.1 Extent to which the contract objectives were reached

To the best of our knowledge, all contract objectives have been achieved (see section 1.2 above).

1.4.2 New knowledge contributed by the project

This project has developed several new **resources** (a table of key thermal impacts and their prevalence in South African rivers; a table of the biological effects of changes in water temperature on river organisms); **maps** (a spatial framework within which air-water temperature models are applied and reference thermographs are generated; a national map of system resilience; and a national map of air temperature - water temperature model accuracy); **databases** (a database of variables likely to indicate system resilience and model accuracy); innovative **tools** (for generating thermal metrics and thermographs; and for generating a Thermal Sensitivity Index and identifying thermally sensitive taxa), **protocols** (a protocol for collecting water temperature data; and a protocol for establishing environmental water temperature guidelines and setting water temperature targets for perennial rivers in South Africa) and **processes** (a screening process to assess thermal risk; and an evaluation process to assess thermal change based on deviation from reference or expected thermal conditions).

1.4.3 How project outcomes will benefit the user (in a national as well as local context)

The products and protocols developed in this project provide water resource practitioners with the necessary knowledge and tools for incorporating water temperature into Resource Directed Measures, including ecological Reserves and Resource Quality Objectives, and Source Directed Controls. These serve the local, regional and national context; and lay the foundation for the establishment of a national water temperature monitoring programme embraced by multiple end-user organisations and stakeholders.

1.4.4 Follow-on actions to be taken

There are two key follow-on actions to be taken:

The first action is to automate the processes developed in this project into a relevant information system that streamlines the output of data required by water resource practitioners needing to incorporate water temperature into Resource Directed Measures, including ecological Reserves and Resource Quality Objectives, and Source Directed Controls. This needs to include the automation of the analysis of water temperature time series data into thermal metrics and thermographs. Automation of these processes will encourage the collection of water temperature data across a large segment of water resource practitioners and allow for the mobilisation of existing water temperature data collected by project team members and other researchers in South Africa.

The second action is to roll out a national water temperature monitoring programme, the need for which has been strongly endorsed by all end-users and stakeholders involved in this project. This will need to be driven by government but will require co-ordination and support of multiple organisations that have a vested interest in tracking long-term change in water temperature. Water and freshwater ecosystems are an integral component of three SDGs, including SDG 6 (Ensure availability and sustainable management of water and sanitation for all), SDG 13 (Take urgent action to combat climate change and its impacts) and SDG 15 (Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification and halt and reverse land degradation, and halt biodiversity loss). A common thread throughout the SDG dialogue is that effective water resource management needs more and better data since data underpin good water governance. Thus: ***Better Data = Better Decisions***.

Key follow-on actions include research activities to address the specific gaps identified during the present study (presented in section 1.6.1 below).

1.5 Capacity development

Capacity development was undertaken both informally and formally, and both individually and collectively via workshops. Two doctoral students formed part of this research project and their studies will provide insight into the effect of climate change, specifically water temperature and flow, on macroinvertebrate assemblages. Appendix 1 lists the capacity development undertaken during the project.

1.6 Recommendations for further research, knowledge dissemination and technology transfer

1.6.1 Further research

- Further validation of the efficacy of the Thermal Sensitivity Index is needed. The Thermal Sensitivity Index will be applied to existing SASS (South African Scoring System) data and the resultant distribution of Thermal Sensitivity Index data will then be evaluated at local, regional and national scales.
- There is scope for regional and seasonal refinement of water temperature models.
- Regional reference thermographs will need to be developed and included in the spatial database framework.

1.6.2 Knowledge dissemination

The knowledge generated through this research has and will continue to be disseminated through several channels, including workshops, presentations, reports and scientific publications. Two multi-stakeholder workshops held in April 2019 were attended by 53 participants from eight organisations. Project team members presented the protocol and tools developed for establishing environmental water temperature guidelines for perennial rivers and for setting water temperature targets in South Africa. Two WRC reports, including a Technical Report and a Technical Manual, once published, will be publicly available. The Technical Manual will serve as a road map for practitioners needing to incorporate water temperature into Resource Directed Measures, including ecological Reserves and Resource Quality Objectives, and Source Directed Controls. The manual speaks directly to several tools, packaged into a toolbox, developed for establishing environmental water temperature guidelines. Project team members have presented at seven conferences and published 24 scientific publications, related to the thermal research undertaken during this and preceding thermal projects on which the current project builds. Appendix 2 lists the knowledge dissemination undertaken by the project team, including conferences attended and scientific publications.

1.6.3 Technology transfer

The main technology transfer is the sharing of the protocols and tools with water resource practitioners.

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- Ms Toni Olsen (DST/NRF intern - 2016)
- Ms Lily Bovim (DST/NRF intern - 2017)
- Mr Philip Frenzel (DST/NRF intern - 2018)
- Ms Melandri Rafferty (DST/NRF intern - 2018)

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1 Introduction

1.1 Background

Southern Africa has been identified as a ‘critical region’ of water stress and existing anthropogenic stresses on freshwater ecosystems are substantial. Freshwaters are particularly vulnerable to global climate change because (i) many species within these fragmented habitats have limited abilities to disperse as the environment changes; (ii) water temperature and availability are climate-dependent; and (iii) many systems are already exposed to numerous anthropogenic stressors (Woodward et al. 2010). Water temperature is a key component of aquatic ecosystems and understanding the role of temperature in these systems and the ecological consequences of changes in water temperature is thus of critical importance.

The establishment of environmental water temperature guidelines that adequately protect aquatic ecosystems and their biota is dependent on an understanding of a river’s thermal signature and the vulnerability of its biota to changes in water temperature. Preceding the current project, water temperature was dealt with as exceedance of percentile values, which was not a satisfactory approach because it ignored issues around how to generate temperature when data are missing, how to analyse temperature time series relative to ecological response, and how to account for regional differences in water temperature patterns. Given the substantial research that has been undertaken on water temperature in the last ten years, there was now an opportunity to develop a more comprehensive method for establishing environmental water temperature guidelines and setting water temperature targets for perennial rivers in South Africa.

In terms of South Africa’s regulatory framework, South Africa’s National Water Act (No. 36 of 1998) provides for the development of a Classification System for water resources, the setting of a Management Class, Resource Quality Objectives (RQOs) and the determination of the ecological Reserve. RQOs are numerical and/or descriptive statements of conditions which should be met in the receiving water resource. The ecological Reserve relates to the volume and quality of water required in a water resource to protect its aquatic ecosystems so as to provide/ maintain the production of natural resources such as healthy habitats and stable and healthy riparian vegetation. Data produced by an ecological Reserve process, which details the objectives to be met for the protection of the ecosystem, are called EcoSpecs. EcoSpecs are clear and measurable specifications of ecological attributes (e.g. flow, water quality, biological integrity) which define the Class. These EcoSpecs, which refer explicitly and only to ecological information, inform the RQOs, which include economic and social objectives. It is with this framework that the current project was undertaken.

1.2 Aims of this project

The overall objective of this project was to translate knowledge generated over ten years of thermal research in South Africa into a protocol for water resource practitioners to incorporate water temperature into Resource Directed Measures, including ecological Reserves and RQOs, and Source Directed Controls for perennial rivers in South Africa. This project thus aimed to bridge the gap between science/research and management/implementation by taking the body of research on water temperature and packaging it in ways that best serves the end users.

The specific aims of this project were as follows:

- To identify the requirements of river managers and practitioners for incorporating water temperature into the ecological Reserve.
- To develop a protocol for collection and/or derivation of water temperature time series data.
- To develop tools for setting water temperature targets for perennial rivers in South Africa.
- To produce a manual for setting water temperature targets for perennial rivers in South Africa.
- To disseminate knowledge on the protocol, tools and guidelines through workshops and discussions.

1.3 Structure of this report

This report provides a general overview of the project and addresses aspects not covered in the technical manual which accompanies this report (Dallas and Rivers-Moore 2019). The following chapters are included in this report:

- **Chapter 1** provides the background to the project, aims and report structure.
- **Chapter 2** provides an overview of water temperature in rivers, thermal impacts, and the effects of thermal changes on river organisms.
- **Chapter 3** documents the engagement with end-users, including the user requirements workshops and the knowledge dissemination workshops.
- **Chapter 4** outlines the protocol for establishing environmental water temperature guidelines and is a summary of the technical manual (***Dallas and Rivers-Moore. 2019: Environmental water temperature guidelines for perennial rivers in South Africa. Volume 2: A technical manual for setting water temperature targets. Water Research Commission Technical Report. From WRC Project K5/2537***).
- **Chapter 5** is the conclusion and recommendations.

2 Water temperature

2.1 Water temperature in rivers

Water temperature, together with flow, is a master variable driving river ecosystems. Flow and thermal regimes vary geographically in response to climate and catchment characteristics and thus both flow and thermal regimes of rivers are likely to vary spatially between sites, reaches, rivers and regions. Water temperature in a river are final values resulting from a number of complex assimilated physical processes (Table 2.1). These can be grouped into **drivers** (which operate beyond the boundaries of the river and control the rate at which heat and water are delivered to the river system); **insulators** (which influence the rate of heat exchange with the atmosphere); and **buffers** (which store heat already in the system and integrate the variation in flow and temperature over time). Key aspects of a river's thermal regime are described by magnitude, timing and duration of thermal events, and frequencies of extreme exceedance events.

Table 2.1. Examples of drivers, insulators and buffers of water temperature in rivers

Drivers	Insulators	Buffers
Solar radiation	River width	Geology
Upstream water temperature	River depth	Groundwater depth
	Topographic shade	Water travel time
	Upland vegetation	Channel morphology

2.2 Thermal impacts

Realistically, very little can be done directly to mitigate impacts on water temperature, and the most practical approach is to mitigate those **insulators** and **buffers** that indirectly affect water temperature. Several human activities modify water temperature in rivers, thereby causing a shift in the water temperature distribution, with an increase or decrease in temperature extremes; or a change in temperature variation. These activities may contribute to increasing the thermal input to a river, reducing the amount of groundwater that serves to moderate stream temperature, or reducing the capacity of a river to absorb heat.

Elevated water temperature is more common and human activities tend to increase temperature rather than decrease it, with the notable exception of bottom release impoundments in summer. Impacts vary spatially and temporally, with some activities resulting in significant thermal impacts for many kilometres, due to either a large temperature change imparted at a specific point (e.g. impoundments) or a more modest temperature change imparted over a large length of river (e.g. extensive loss of riparian shading). From a temporal perspective, water abstraction in summer, during natural low-flow periods in winter rainfall regions will have a greater thermal impact compared to abstraction in winter. Many impacts are moderate in degree and spatial extent (e.g. localised cutting of riparian vegetation), causing comparatively localised impacts. Common point and non-point thermal impacts are listed in Table 2.2.

Further detail on each impact, their prevalence in South African rivers, mitigation options, and the effects of temperature changes on physico-chemical parameters (water quality) are provided in the technical manual.

Table 2.2. Thermal impacts (point- and non-point source)

Thermal Type	Thermal Impact
Point-source	Heated water from power plants
	Altered (heated or cooled) effluent from industries
	Heated effluent from mines, including mine dewatering
	Treated wastewater from waste water treatment works and water treatment works
	Flow modification (e.g. river regulation and impoundments)
	Surface water abstraction
	Flow augmentation (e.g. inter-basin water transfer)
	Groundwater abstraction
	Agricultural/irrigation return flows
Non-point source	Land-use change – urban runoff/catchment hardening
	Modification of riparian vegetation
	Modification of channel morphology
	Global climate change

2.3 Effects of thermal changes on river organisms

Biological effects of changes in water temperature (and flow) on river organisms may include individual- and population-level modifications such as alteration of individual life history patterns, increases in the number and spread of invasive and pest species (such as blackfly), increase in waterborne and vector-borne diseases (cholera, malaria, etc), extinction of vulnerable species, shifts in species distribution and range, and changes in communities and aquatic biodiversity. Each biological effect may be categorized as physiological, metabolic, phenological, reproductive, behavioural or ecological (Table 2.3). Further details on the biological effects and the response variables in relation to temperature are described in the technical manual.

Table 2.3. Biological effects resulting from thermal change in rivers. Response variables are given for each category including physiological, metabolic, phenological, reproductive success and fitness, behavioural, and ecological (from Dallas and Ross-Gillespie 2015)

Major effects	Response variables
Physiological and metabolic	Performance curves
	Growth rates
	Size at emergence
	Secondary productivity and assimilation
	Respiration
Phenological	Total development time
	Voltinism flexibility
	Timing and duration of emergence
	Timing of fish spawning
Reproductive success and fitness	Fecundity
	Rates and success of egg development and hatching
	Juvenile survival and recruitment
Behavioural	Migration
	Drift
Ecological	Species richness
	Species composition
	Density
	Distribution patterns

3 Engagement with water resource practitioners

3.1 Understanding end-user requirements

Protocols and tools need to speak to the needs of the end-users who are mandated to apply them. For this reason, the project team engaged with end-users in two workshops at the start of the project (October 2016) to gather feedback from a regional and national organisational perspective.

Prior to the workshops, a questionnaire was distributed to end-users to identify the extent to which water temperature had been included in ecological Reserve studies, and to determine the requirements of river managers and practitioners for incorporating water temperature into Reserve studies, including the setting RQOs. The results of this questionnaire are summarised in **Appendix 3.**

The first User Requirements workshop was held at the Department of Water and Sanitation (DWS), Bellville, Cape Town; and the second at the DWS, Roodeplaat, Pretoria. The aim of the workshops was to determine the requirements of river managers and practitioners for incorporating water temperature in Reserve studies, including the setting of RQOs. Participants at each workshop and presentations given are provided in **Appendix 4.**

Several points emerged from the workshops, summarized below. These were used to guide the refinement of the protocol, tools and technical manual.

- A recognition that there is a need to monitor water temperature for trend (i.e. long-term data at selected sites) versus for end-of-pipe impacts.
- Water temperature needs to be routinely monitored at strategically selected national sites. DWS needs to action water temperature monitoring. There was support for the inclusion of water temperature monitoring at River Ecostatus Monitoring Programme sites and the Ecological Water Requirements sites.
- A conservative approach was advocated by strategically selecting sites in areas where data and capacity already exist. The suggestion was adopted that a number of sites in selected Western Cape rivers be identified as a starting point.
- Water temperature data is needed to improve water-air temperature models and develop reference thermographs for different thermal regions. Modelling present-day water temperature data is difficult – there is a clear need for logged water temperature data. Linked to this is the need to improve the capacity for scenario modelling of thermal responses to altered river conditions; e.g. the ability to predict how water temperature will change with changes in flow.

- Given the scarcity of water temperature data, the option of having a two-tiered approach needs to be explored, from broad national level guidelines, down to site-specific, stressor-specific guidelines where data are available.
- There is a need to develop a screening process that allows practitioners to easily determine if water temperature should be examined at a particular site/reach/river, i.e. a description of activities that trigger the need for a thermal response. This should include aspects such as the likely thermal impact of an activity (important especially in Source Directed Controls and licensing) and the sensitivity of the site/reach/river and its biota (e.g. endangered cold-water fish species) to thermal change. There is a need to develop a rating index for different activities in terms of the likely thermal effect of different thermal stressors. This could also take the form of a matrix of thermal stressors, with an environmental context that unpacks which river systems are more or less sensitive to thermal changes.
- There was recognition of the potential strength in cooperation between institutions and organisations to establish long-term water temperature monitoring sites. The Protected Area Networks and conservation organisations (including SANParks, CapeNature, etc) should be considered as a spatial framework within which water temperature is routinely monitored. This would be especially valuable for determination of thermal reference envelopes and would serve as a benchmark for monitoring the long-term effect of global climate change on river systems.

3.2 Knowledge dissemination workshops

Two workshops were held during April 2019 to present the protocol and tools developed for establishing environmental water temperature guidelines for perennial rivers and for setting water temperature targets in South Africa. These workshops were attended by 53 participants from eight organisations. The protocol and tools were packaged into the manual, which was provided to workshop participants prior to the workshops. The aim of the workshop was to gather feedback from a regional and national organisational perspective on the protocol and tools. The first workshop was held at the DWS, Bellville, Cape Town, and the second workshop was held at the DWS, Head Office, Pretoria. Participants at each workshop and presentations given are provided in **Appendix 5.**

The project team provided an overview of the introduction and then led the workshop participants through the Screening Process and the Evaluation Process. Both workshops were interactive with participants asking questions and providing feedback throughout.

4 A protocol for establishing environmental water temperature guidelines

TECHNICAL MANUAL:

Dallas and Rivers-Moore. 2019. Environmental water temperature guidelines for perennial rivers in South Africa. Volume 2: A technical manual for setting water temperature targets in South Africa. Water Research Commission Technical Report. From WRC Project K5/2537.

4.1 Background to the technical manual

To enable water resource practitioners to set water temperature targets for perennial rivers in South Africa, a technical manual has been produced that serves as a road map for practitioners needing to incorporate water temperature into Resource Directed Measures, including ecological Reserves and RQOs, and Source Directed Controls. It speaks directly to several tools, packaged into a toolbox, developed for establishing environmental water temperature guidelines. The protocol was informed by the end-user requirements workshops, in particular the need for a screening process, which has been integrated into the protocol.

The technical manual is a resource to provide practitioners with the necessary background and understanding of the importance of water temperature in South African rivers, including the effects of thermal changes on river organisms; an overview of thermal impacts on rivers and ways to manage and mitigate thermal impacts; guidance on when water temperature should be considered (Screening Process), and a protocol for establishing environmental water temperature guidelines (Establishing Reference Indicators of Thermal Alteration (thermal metrics) and a Reference Thermograph) and evaluating deviation from established guidelines (Evaluating deviation from Reference thermal metrics and a Reference Thermograph). This manual aims to equip water resource practitioners with the necessary knowledge and tools for establishing environmental water temperature guidelines and evaluating thermal impacts on perennial rivers in South Africa. It is hoped that this road map and toolbox will serve to mobilise routine monitoring of water temperature at a local, regional and national scale.

The use of environmental water temperature guidelines may be both proactive and reactive. The former relates to the establishment of guidelines to serve as a benchmark for future evaluation of thermal change and may include an assessment of trend; while the latter may be the direct response to an existing thermal impact or proposed thermal impact for which a user has submitted a water use licence application (Figure 4.1).

For site-specific impacts, aspects such as the likely thermal impact of an activity (important especially in Source Directed Controls and licensing) and the sensitivity of the site, reach or river and its river organisms (e.g. endangered cold-water fish species) to thermal change, are considered. In contrast, sites identified as part of a national water temperature monitoring programme will require long-term baseline data that are assessed every one to five years for detection of trends away from the reference condition (Table 4.1) in response to factors such as global climate change and water abstraction.

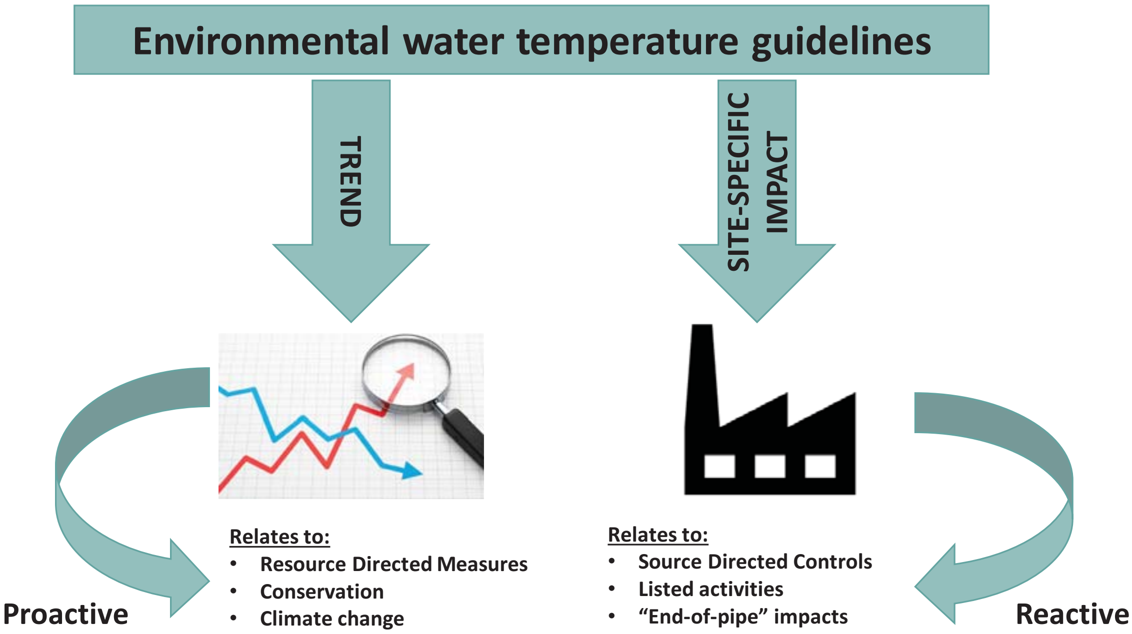

Figure 4.1. Environmental water temperature guidelines for site-specific impacts and trend analyses

Table 4.1. Site-specific impacts versus trend away from a desired state

Site-specific point source impacts	Trend away from a desired state
Requires a departure from a predetermined condition (could be a reference condition)	Requires long-term baseline data and monitoring
Mitigation needs a spatial component (downstream impact) and temporal component (time to normalise)	Needs to be statistically tested for departure against a defendable threshold

The following sections summarise the two processes to be followed for establishing environmental water temperature guidelines, namely the:

- Screening Process, and
- Evaluation Process, which includes two sub-components: 1) Establishing Reference Indicators of Thermal Alteration (thermal metrics) and a Reference Thermograph, and 2) Evaluating deviation from Reference thermal metrics and a Reference Thermograph.

4.2 Water temperature data

There is very little continuous time series of sub-daily water temperature data available for South African rivers, particularly where these data are longer than one full thermal year. We estimate that these data are available for approximately 1% of the quinary sub-catchments covering South Africa. The situation is an order of magnitude better for air temperature data, although the 973 air temperature stations listed in Schulze and Maharaj (2004) cover only 10.7% of the quinary sub-catchments. Even with these data, translation of air temperature to water temperature requires suitable simple linear regression equations. Because of the scarcity of these data, but with a requirement to provide a consistent national framework for evaluating the thermal ecological Reserve, we developed a spatial framework based on quinary sub-catchments, with corresponding data per quinary that provides information on system resilience and potential model accuracy. Reference thermographs will in the future be generated for the 10.7% of quinary sub-catchments where air temperature data exist.

4.3 The Screening Process

Not all sites, reaches and rivers need to be managed for water temperature. Asking the right questions allows one to evaluate the importance of maintaining an appropriate thermal regime at a site, reach or river. Practitioners need to determine whether or not water temperature should be considered at a particular site, be it for setting an environmental water temperature guideline or evaluating the potential effect of a thermal impact. A workflow diagram has been generated to guide the practitioner during the screening process.

The three key questions to address when assessing whether water temperature needs to be considered, before quantifying thermal stress and assessing risk, include:

- How resilient is the site, reach or river to changes in water temperature? = Evaluating system resilience
- Are there other hydrological, physico-chemical (water quality) or habitat considerations that could magnify or diminish thermal impacts?
- How sensitive are the river organisms?

The spatial scale of screening may vary from site to reach to river, depending on the size of the river. So, for example, a site on a large fifth-order river would be screened at site-scale, while a small first-order tributary may be screened at the river-scale.

The final stage of the screening process is an assessment of thermal stress in terms of risk and a calculation of risk needs to be undertaken by water resource practitioners when evaluating thermal impacts at a specific site. A thermal risk assessment matrix has been developed for this. This informs whether water temperature needs to be further examined at a site, in which case the water resource practitioner continues on with the Evaluation Process.

4.4 The Evaluation Process

The evaluation process is sub-divided into two components: 1) establishing Reference Indicators of Thermal Alteration (thermal metrics) and a Reference Thermograph, and 2) evaluating deviation of water temperature monitoring data from Reference thermal metrics and a Reference Thermograph, including the determination of the Ecological Category (A to F). This has been developed within the context of the Ecological Limits of Hydrologic Alteration framework, a framework widely regarded as being suitable for generating hypotheses regarding ecological response to system changes.

The protocol also includes details of collecting water temperature data, the spatial framework within which the reference thermographs are generated, and calculation of model accuracy.

The tools will ultimately be integrated into the Freshwater Biodiversity Information System (www.freshwaterbiodiversity.org) and will generate a Thermal Report Card that integrates several outputs which water resource practitioners need to incorporate water temperature into Resource Directed Measures, including ecological Reserves and Resource Quality Objectives, and Source Directed Controls. The following output components will be summarised in a Thermal Report Card for a specific site, using an automated process:

- Site information, including a map, photograph (if available) and details about the site such as Water Management Area, catchment, ecoregion, geomorphological zone, etc.
- Details on climate, Department of Water and Sanitation hydrological and water quality gauging stations, hydrological regions and flow regime types.
- Screening process information, including details of system resilience, hydrological, physico-chemical (water quality) and habitat considerations, sensitivity of river organisms, thermal impact(s) and thermal risk assessment.
- Evaluation process information on availability of reference and monitoring water temperature data, Indicators of Thermal Alteration showing deviation from reference, model accuracy score and accuracy radar plot, and a reference thermograph showing deviation of monitored water temperature data when available.

4.5 Case studies

4.5.1 Case study 1: Hypolimnetic discharge of water from an impoundment

Narrative

The thermal assessment protocol was applied using a case study for paired sites from the Western Cape (Witte River; un-impacted site -33.637090 °S; 19.107890 °E) and Holsloot River (downstream of an impoundment; impacted site -33.837930 °S; 19.256310 °E). Both sites are located on upland river segments within 25 km of each other on parallel tributaries of the Breede River, and 230m apart in altitude (Witte = 660mamsl; Holsloot = 430mamsl). Based on altitudinal differences, it was expected that the impacted site would be warmer than the reference site. However, the site on the Holsloot River is located downstream of the Stettynskloof Dam which is the water supply for the town of Worcester. Downstream flow requirements are met through hypolimnetic releases, having been redesigned in 1981. Economically, the altered flow conditions have enabled a trout industry – the Dwarsberg Trout Hideaway - to flourish. Ecologically, the dam has resulted in point-source thermal pollution due to flow modification.

Assessment of thermal condition

Hourly water temperature data were available for comparable sites on the Holsloot and Witte Rivers for the period 1 January – 31 December 2009. Both sites exhibited almost identical resilience (Total Resilience Scores = 2.85 and 3.01 respectively) and model accuracy scores (Model Accuracy Scores = 1.70 and 1.82 respectively) (Figure 4.2), highlighting that these sites may be treated similarly. Visual inspection of the hourly data indicated considerable differences in the thermal regimes of each site (Figure 4.3). To evaluate whether each site was meeting the requirements of the thermal ecological Reserve, the steps in the protocol required the calculation of thermal metrics using the Indicators of Thermal Alteration approach. Next, monitoring site thermographs were plotted using seven-day moving averages of mean daily water temperature for each site. These were plotted within a reference thermal envelope based on thermal regimes for ten reference sites that all had statistically similar thermal regimes (Rivers-Moore et al. 2013a).

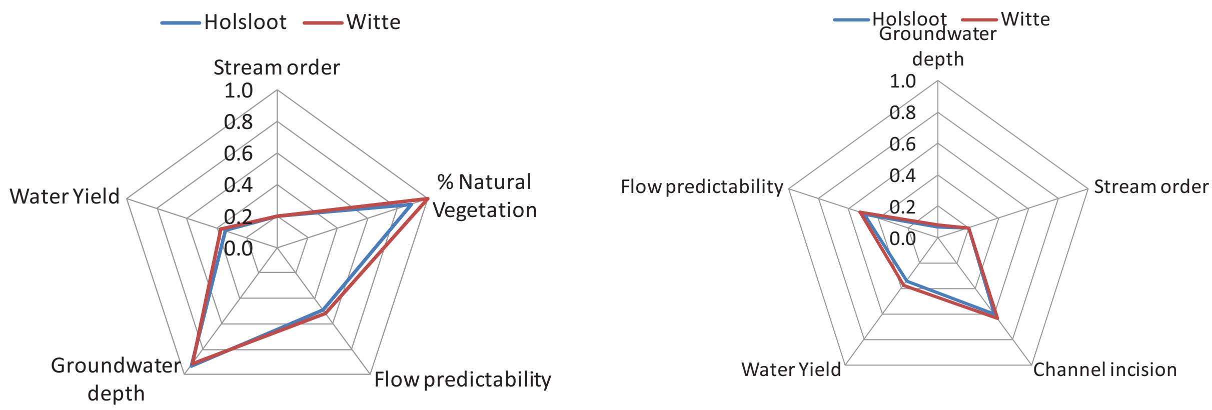

Figure 4.2. Radar plots showing contribution of metrics to resilience (left) and model accuracy (right) scores for the Holsloot and Witte Rivers

In terms of the Indicators of Thermal Alteration data, the monitoring site was three times cooler than the reference condition based on annual heat units. Whereas winter temperature was marginally elevated (<1°C for weekly, monthly and seasonal moving averages of daily minima), major impacts are highlighted by considerably suppressed summer water temperature (Table 4.2). The thermal metrics therefore illustrate that the thermal impacts relate to cooling effects. To define the ecological categories, the thermographs were assessed against the thermal reference envelope. By way of comparison, the thermal regime for the Witte River has an Ecological Category of "A" (Figure 4.4). In contrast, the Holsloot River has a thermal Ecological Category of "A" for the winter months (May-September) that deteriorates to an "F" for the summer months (October – April) (Figure 4.5).

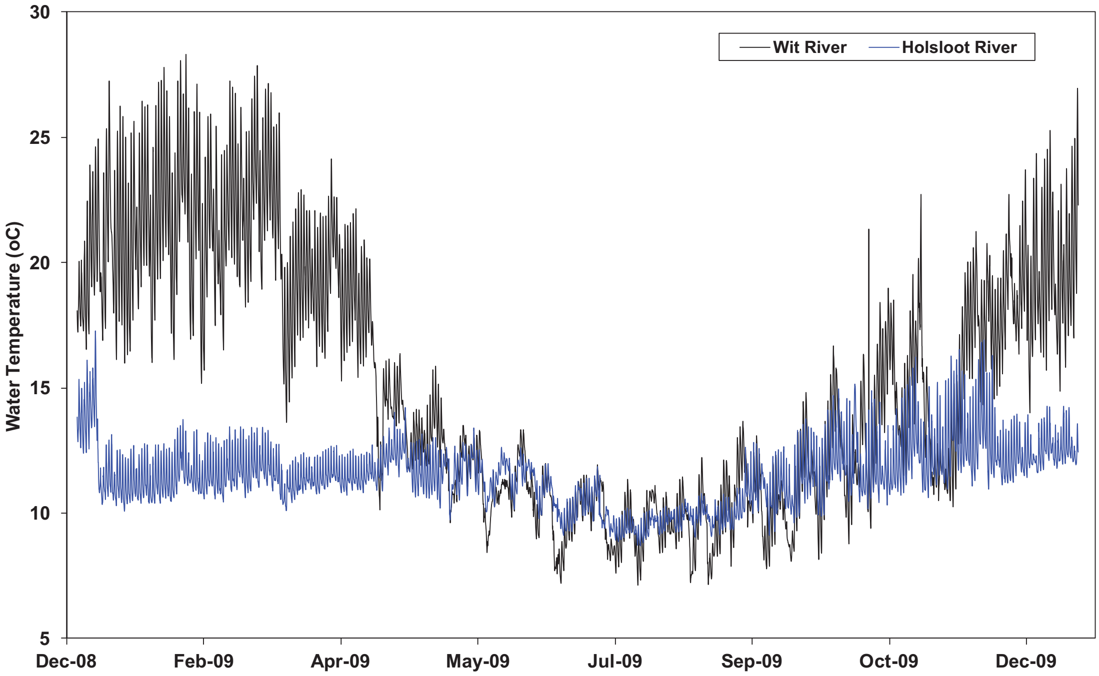

Figure 4.3. Time series plot of hourly water temperature for the Holsloot and Witte Rivers

Table 4.2. Comparison of metrics for reference group versus monitoring site (Holsloot River), where * indicates outside reference range, with blue (cooler reference) or red (warmer than reference)

Thermal Metric	Reference Site	Monitoring Site
Mean Annual Temperature (MAT)	15.04	11.48*
Standard Deviation of MAT	4.10	1.08*
Annual coefficient of variability	27.23	9.38*
Predictability	0.59	0.79*
Mean of daily range	3.24	1.87
Mean of annual minima	13.62	10.74*
Mean of annual maxima	16.86	12.62*
Degree days	1838.92	541.42*
Mean7*	22.14	14.12*
Min_7*	7.85	8.95*
Min_30+	8.63	9.19
Min_90+	9.20	9.59
Max7*	24.98	16.10*
Max_30+	23.91	15.25*
Max_90+	23.38	14.38*

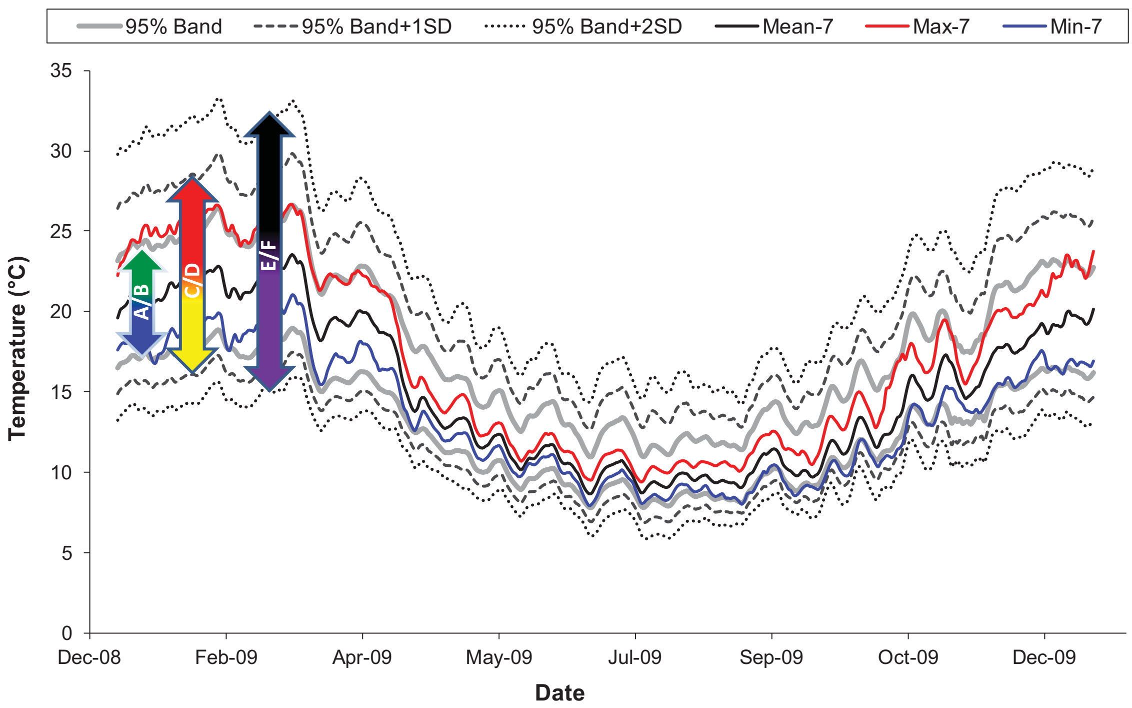

Figure 4.4. Thermograph of Witte River plotted within thermal reference envelope, and showing the Ecological Categories

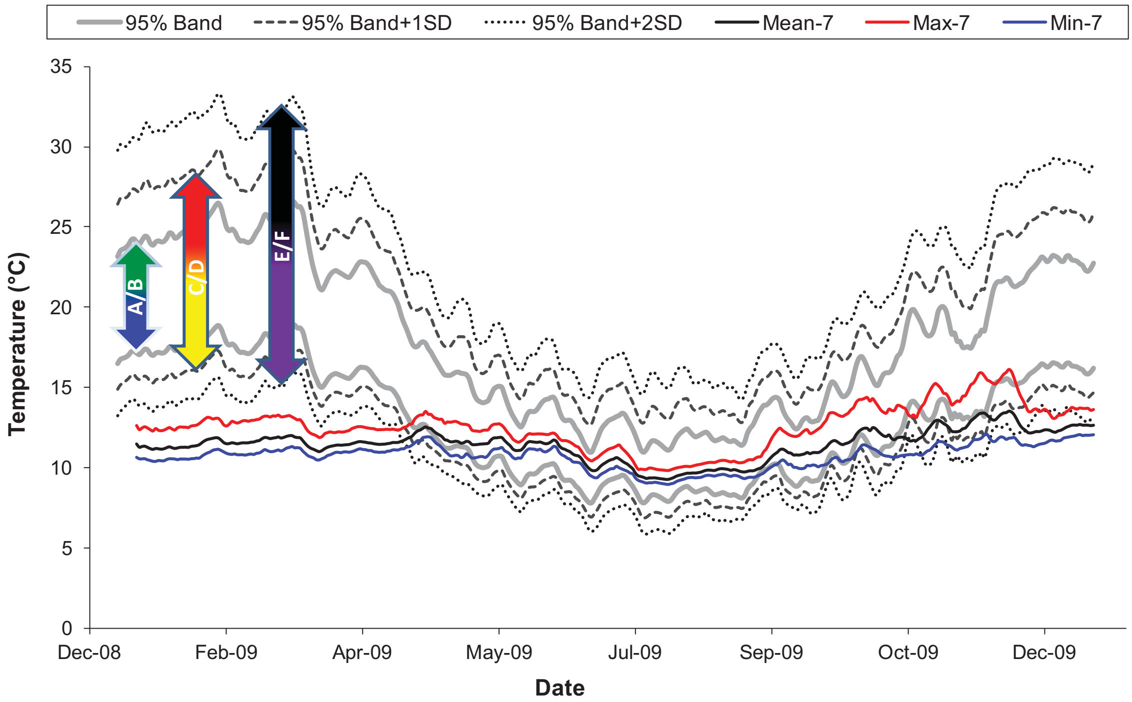

Figure 4.5. Thermograph of Holsloot River plotted within thermal reference envelope, and showing the Ecological Categories

Mitigation options

The thermal assessment provides specific guidelines for the timing and the duration of mitigation measures, should these be desired. Depending on the preferred Ecological Category, and relative cost-benefits of ecological restoration versus economic benefits of the fishing industry, mitigation could be defined in terms of the following:

- May – September: Zero management interventions.
- October – April require elevation of mean daily water temperature by approximately 10°C. Mitigation measures could include the construction of an off-channel holding dam to allow water temperature to equilibrate with summer air temperature; or multi-level release valves could be retroactively fitted to allow for hypolimnetic releases during the summer months.

4.5.2 Case study 2: Climate change impacts on pest blackfly outbreaks, Orange River

Narrative

Under current flow and water temperature conditions, outbreaks of adult pest blackfly along an 800km segment of the middle and lower Orange River cause in excess of R500 million in losses to the stock farming industry alone (Rivers-Moore et al. 2014). Larval blackfly of the main pest species, *Simulium chutteri* (Diptera: Simuliidae), are multivoltine, and thrive under high flows where water temperature is already favourable throughout the year in the Orange River (Rivers-Moore and Palmer 2018). Previous research on blackfly outbreak dynamics in South Africa estimates that a 2°C increase in water temperature could result in blackfly populations increasing by a twenty-fold factor annually, in addition to the number of generations increasing by 25% annually (Rivers-Moore et al. 2013b). This scenario excludes the compound impact of a predicted 60% increase in flow in the Orange River for intermediate future climate change scenarios projected for years 2020 to 2070 (Rivers-Moore and Hill 2018).

Assessment of thermal condition

The Orange River in the vicinity of Upington was characterised in terms of resilience and model accuracy. According to our metrics, the Orange River in this quinary catchment shows relatively high resilience (Total Resilience Score = 3.30), with water temperature models likely to be relatively accurate (Model Accuracy Score = 2.75) (Figure 4.6). In this context, the water yield metric score is misleading because, while in a desert environment, river flows are high due to large upstream contributions to high volume (median flows > 100 $m^3.s^{-1}$) stable flows. This translates into a reference thermal envelope with relatively narrow standard deviations around the 95% confidence interval (Figure 4.7). In other words, there is a relatively small margin of error between Ecological Categories A to F. With an assumed 2°C increase in mean daily water temperature, the thermal ecological Reserve is thus predicted to deteriorate from an overall “A” category to a predominantly “F” category (Figures 4.7-8). Depending on whether the increased number of blackfly generations or population size are used to simplistically calculate additional future impacts due to global climate change on the livestock industry in the middle Orange River, the cost of thermal ecological Reserve failure potentially equates to R125 million (number of blackfly generations only) or R9,5 Billion (number of blackfly generations and population size).

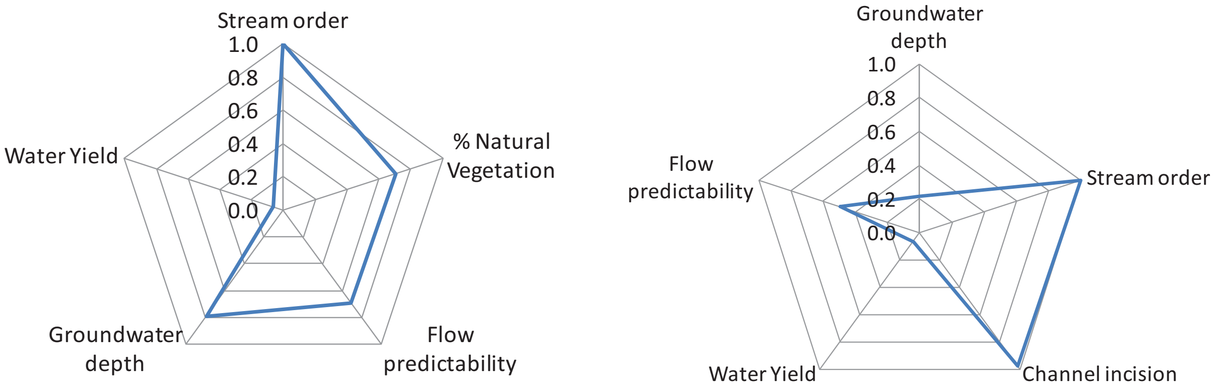

Figure 4.6. Radar plots showing contribution of metrics to resilience (left) and model accuracy (right) scores for the lower Orange River at Upington

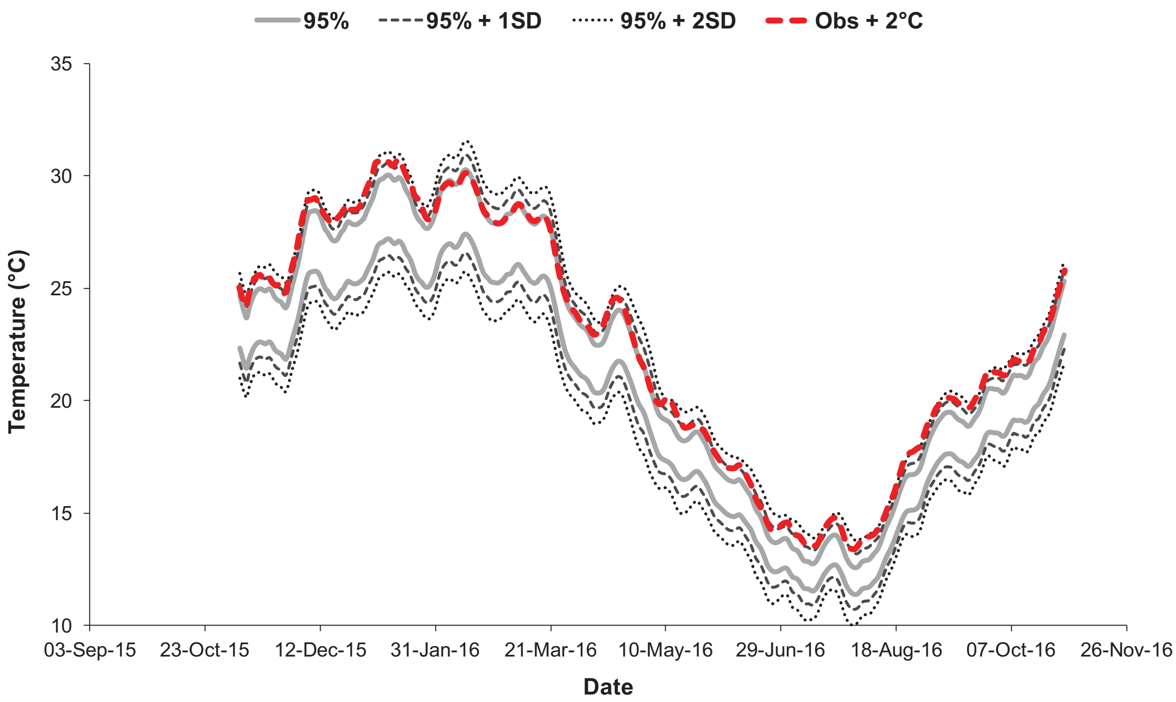

Figure 4.7. **Annual thermograph of water temperature at Upington plotted with the thermal reference envelope based on current water temperature for the lower Orange River at Upington. Thermograph values reflect a seven-day moving average of mean daily water temperature, assuming a 2°C increase from current water temperature**

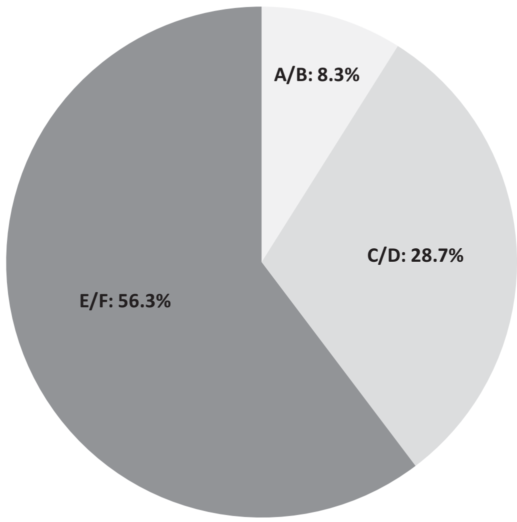

Figure 4.8. **Percentage of time over one year of mean daily water temperature + 2°C within the Ecological Categories for Upington**

Mitigation options

The blackfly problem along the Orange River has been described as a "wicked problem" by Rivers-Moore and Hill (2018), because of the mutually exclusive competing goals of multiple stakeholders within this region. For example, winter flow reductions downstream of the Van Der Kloof Dam would be an effective blackfly control option as a regional priority; however, high winter flows are required for hydro-electric power generation to feed into the national power grid. Mitigation options are thus limited without ongoing stakeholder engagement, and trade-offs between different regional industries.

4.5.3 Case study 3: Regional application of thermal reference envelopes

Narrative

Regional differences in various landscape and climatic variables, such as solar radiation, groundwater depth and incision, result in unique thermal signatures between and within rivers across South Africa. This has implications for how reference thermographs are generated. Furthermore, given the relative paucity of even short-term (< two years) daily water temperature data, the options of generating reference thermographs are limited. The best source of data is thus to use daily minimum/maximum air temperature as the basis for simulating mean daily water temperature. Here, we explore the implications of these regional differences on the applicability of a generic thermal reference envelope; and of using simulated mean daily water temperature to describe a reference thermograph.

Assessment of thermal reference condition

We generated reference thermal envelopes for five sites in the Berg River catchment, corresponding with five thermal groups identified by Rivers-Moore et al. (2013a), with an additional site for the Orange River at Upington, based on a thermal group identified by Rivers-Moore and Hill (2018). Results indicate a variety of reference thermal envelope shapes, with varying A to F bandwidths, within and across catchments (Figure 4.9).

Next, using a space-for-time substitution, we generated an average year of mean daily air temperature for Kersefontein Farm on the Berg River. Maximum and minimum daily air temperature for 1 January 1950 to 31 December 1999 were obtained from Schulze and Maharaj (2004) for the station 0061298_W. Mean daily air temperature was calculated as the average of daily minimum and maximum air temperature values; each day's air temperature over fifty years was averaged to derive a "typical year" of mean daily air temperature. Mean daily water temperature was simulated from these values using Equation 1. We correlated, observed and simulated mean daily water temperature, and plotted both of these time series within a thermal reference envelope for the relevant thermal group (Group 12; see Figure 4.9 D).

$$WT_{mean} = 3.278 + 0.899 * AT_{mean} \quad [1]$$

The correlation between observed and simulated mean daily water temperature was good ($R^2 = 0.91$; Figure 4.10). Whereas observed mean daily water temperature was within an "A" Ecological Category, the simulated mean daily water temperature was cooler than the observed values and extended over classes A, B and C (Figure 4.11).

Mitigation options

We conclude that the shape of thermal reference envelopes will vary regionally, and that, consequently, thermal reference data will need to be site-specific. The varying widths of the confidence intervals in the reference envelopes means that the thermal ecological Reserve is more likely to be exceeded in certain rivers than in others. For example, thermally stable rivers, such as big rivers and mountain streams, will be more likely to undergo exceedances in their thermal reserves than in more variable rivers. Nevertheless, it is possible to calculate a reference thermograph for mean daily water temperature using a time-for-space substitution of mean daily air temperature data. However, this will be at the expense of data confidence. Ultimately, there is no substitute for collecting long-term observed daily water temperature.

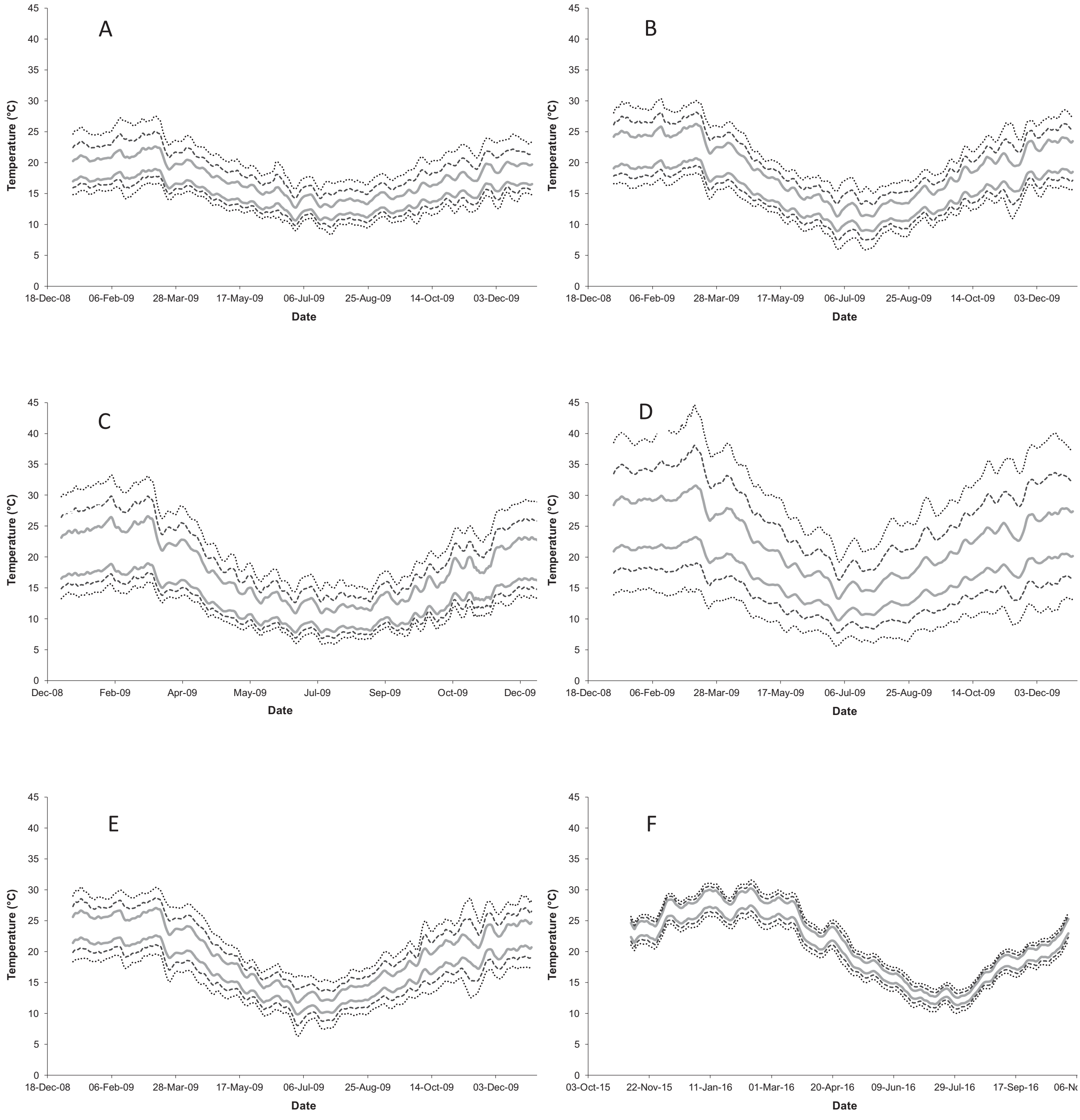

Figure 4.9. Reference thermal envelopes for six thermal types within South Africa: A = Group 5; B = Group 7; C = Group 10; D = Group 12; E = Group 13; F = Middle Orange River (Upington)

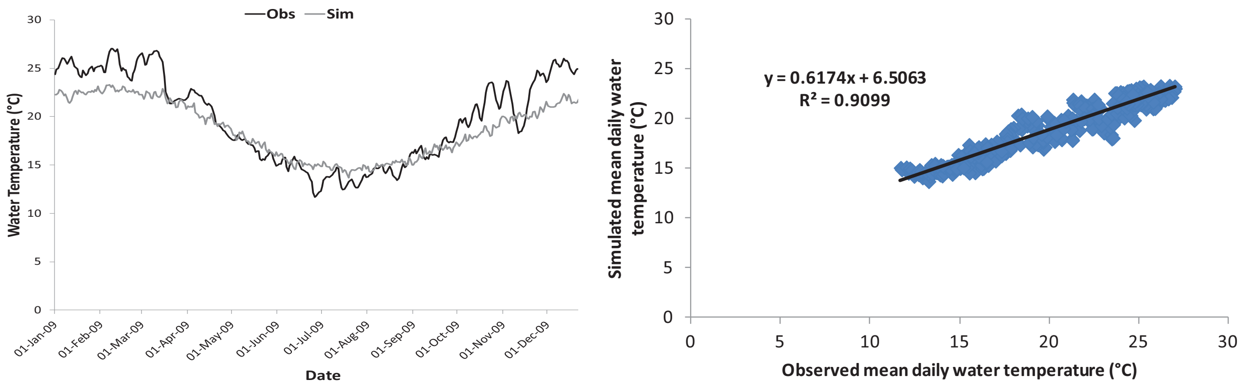

Figure 4.10. Time series plot of observed mean daily water temperature versus mean daily water temperature simulated from air temperature

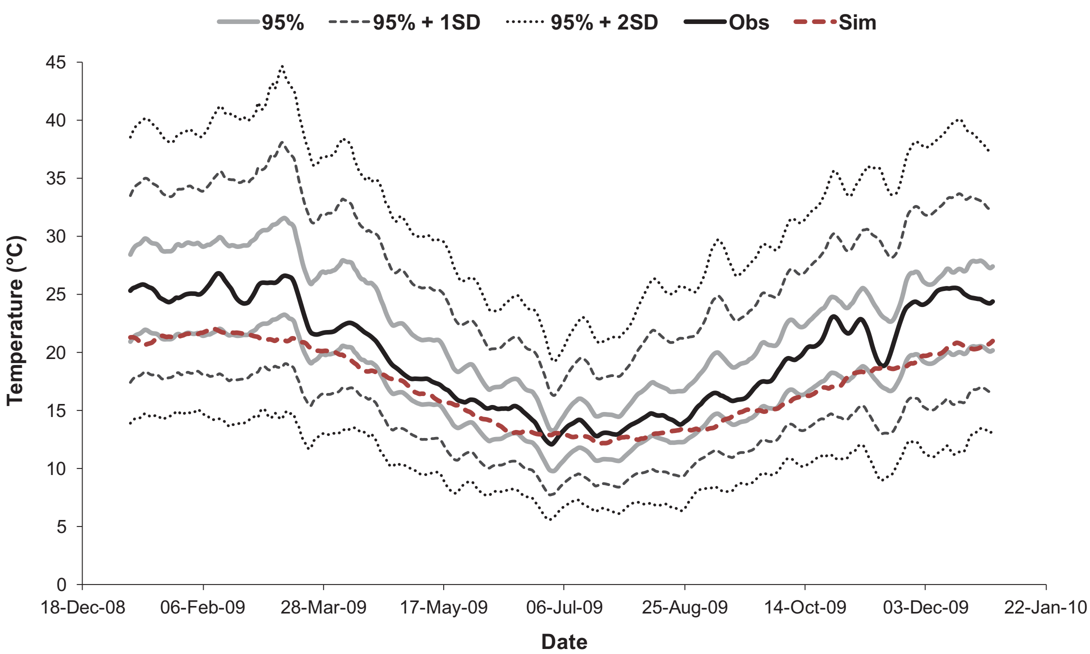

Figure 4.11. Thermographs of observed and simulated mean daily water temperature plotted within thermal reference envelope for Group 12, and showing Ecological Categories

5 Conclusion and Recommendations

This project has developed several new **resources** (a table of key thermal impacts and their prevalence in South African rivers; a table of the biological effects of changes in water temperature on river organisms); **maps** (a spatial framework within which air-water temperature models are applied and reference thermographs are generated; a national map of system resilience; and a national map of air temperature - water temperature model accuracy); **databases** (a database of variables likely to indicate system resilience and model accuracy); innovative **tools** (for generating thermal metrics and thermographs; and for generating a Thermal Sensitivity Index and identifying thermally sensitive taxa); **protocols** (a protocol for collecting water temperature data; and a protocol for establishing environmental water temperature guidelines and setting water temperature targets for perennial rivers in South Africa) and **processes** (a screening process to assess thermal risk; and an evaluation process to assess thermal change based on deviation from reference or expected thermal conditions). The products and protocols developed in this project provide water resource practitioners with the necessary knowledge and tools for incorporating water temperature into Resource Directed Measures, including ecological Reserves and RQOs, and Source Directed Controls. These serve the local, regional and national context; and lay the foundation for the establishment of a national water temperature monitoring programme embraced by multiple end-user organisations and stakeholders.

There are two key follow-on actions recommended by the project team. The first action is to automate the processes developed in this project into a relevant information system that streamlines the output of data required by water resource practitioners needing to incorporate water temperature into Resource Directed Measures, including Ecological Reserves and RQOs, and Source Directed Controls. This needs to include the automation of the analysis of water temperature time series data, into thermal metrics and thermographs. Automation of these processes will encourage the collection of water temperature data across a large segment of water resource practitioners and allow for the mobilisation of existing water temperature data collected by project team members and other researchers in South Africa.

The second action is to roll out a national water temperature monitoring programme, the need for which has been strongly endorsed by all end-users and stakeholders involved in this project. This will need to be driven by government but will require co-ordination and support of multiple organisations that have a vested interest in tracking long-term change in water temperature. Water and freshwater ecosystems are an integral component of three SDGs, including SDG 6 (Ensure availability and sustainable management of water and sanitation for all), SDG 13 (Take urgent action to combat climate change and its impacts) and SDG 15 (Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification and halt and reverse land degradation, and halt biodiversity loss). A common thread throughout the SDG dialogue is that effective water resource management needs more and better data since data underpin good water governance. Thus: ***Better Data = Better Decisions***. This is becoming increasingly urgent given global climate change, which affects river ecosystems fundamentally through changes in water temperature and discharge, as well as exacerbating existing stresses on aquatic ecosystems.

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Appendix 1 Capacity development

Capacity development was undertaken both informally and formally, and both individually and collectively via workshops. Two doctoral students formed part of this research project and their studies will provide insight into the effect of climate change, specifically water temperature and flow, on macroinvertebrate assemblages.

Ms Nonkanyiso Zungu - PhD at University of Cape Town (2016 – 2019). Supervised by Dr Helen Dallas, Prof Jenny Day and Dr Cecile Reed. Title of thesis: The effects of climate change on mountain stream macroinvertebrate species assemblage in the Cape Floristic Region of South Africa.

Mr Pafanani Ramulipho - PhD at University of Venda (2016 – 2019). Supervised by Dr Stefan Foord, Dr Nicholas Rivers-Moore and Dr Helen Dallas. Title of thesis: Modelling flow and water temperature in the Luvuvhu River catchment and their impact on macroinvertebrate assemblages.

Several interns from the FRC assisted with field surveys, data consolidation and analysis, gaining valuable experience in the process, including:

- Ms Toni Olsen (DST/NRF intern - 2016)
- Ms Lily Bovim (DST/NRF intern - 2017)
- Mr Philip Frenzel (DST/NRF intern - 2018)
- Ms Melandri Rafferty (DST/NRF intern - 2018)

Appendix 2 Knowledge dissemination at conferences and scientific publications

Project team members have presented on components of the project at seven conferences, including:

- Dallas HF and Rivers-Moore NA. 2019. Environmental water temperature guidelines for perennial rivers: A protocol and tools for setting water temperature targets in South Africa. Oral presentation at the Southern African Society for Southern Africa conference, Limpopo. July 2019.
- Ramulifho PA and Foord S. 2016. Environmental Flow Requirements and Response of Macro-Invertebrate Populations in the Luvuvhu River Catchment. Poster presentation at the international long-term ecological research network. 1st open science meeting, Skukuza. October 2016.
- Ramulifho PA and Foord S. 2017. Environmental Flow Requirements and Response of Macro-Invertebrate Populations in the Luvuvhu River Catchment. Poster presentation at the Zoological Society of Southern Africa conference, Pretoria. July 2017.
- Ramulifho PA and Foord S. 2017. Variability analyses of long-term flow and water temperature regimes in the Luvuvhu River Catchment. Poster presentation at the International Water Association, Skukuza. October 2017.
- Ramulifho PA, Rivers-Moore NA, Dallas H, Foord SH. 2017. A conceptual framework towards more holistic freshwater conservation planning through incorporation of stream connectivity and thermal vulnerability. Oral presentation at the Symposium of Contemporary Conservation Practice, Howick. November 2017.
- Ramulifho PA, Rivers-Moore NA, Roux H, Foord SH. 2018. Stream flow trend analyses using daily and sub-daily flow data in the Luvuvhu River catchment. Oral presentation at the Global Change conference, Polokwane. December 2018.
- Ramulifho PA, Rivers-Moore NA, Roux H, Foord SH. 2019. The influence of flow and temperature on Mayfly (Ephemeroptera, Insecta) community structures in the Luvuvhu River Catchment. Oral presentation at the Southern African Society for Southern Africa conference, Limpopo. July 2019.

Twenty-four scientific publications, related to the thermal research undertaken during this and preceding thermal projects on which the current project builds, have been published. Several of these have been widely cited in international literature with published methods taken up by other countries. They are listed alphabetically below:

Dallas HF. 2008. Water temperature and riverine ecosystems: An overview of knowledge and approaches for assessing biotic responses, with special reference to South Africa. *Water SA* 34(3): 393-404.

Dallas HF. 2016. The influence of thermal history on upper thermal limits of two species of riverine insects: the stonefly, *Aphanicerca capensis*, and the mayfly, *Lestagella penicillata*. *Hydrobiologia* 781(1): 95-108.

Dallas HF and Ketley ZA. 2011. Upper thermal limits of aquatic macroinvertebrates: comparing Critical Thermal Maxima with 96-LT_{50} values. Journal of Thermal Biology 36(6): 322-327.

Dallas HF and Rivers-Moore NA. 2011. Micro-scale heterogeneity in water temperature. *Water SA* 37(4): 505-512.

Dallas HF and Rivers-Moore NA. 2012. Critical Thermal Maxima of aquatic macroinvertebrates - towards identifying bioindicators of thermal alteration. *Hydrobiologia* 679(1): 61-76.

Dallas HF and Rivers-Moore NA. 2014. Ecological consequences of global climate change for freshwater ecosystems in South Africa. *South African Journal of Science* 110 (5/6): 48-58.

Dallas HF and Rivers-Moore NA. 2018. Temporal thermal refugia and seasonal variation in upper thermal limits of two species of riverine invertebrates: the amphipod, *Paramelita nigroculus*, and the mayfly, *Lestagella penicillata*. *Aquatic Ecology* 52(4): 333-349.

Dallas HF and Ross-Gillespie V. 2015. Sublethal effects of temperature on freshwater organisms, with special reference to aquatic insects. *Water SA* 41(5): 712-726.

Eady BR, Hill T and Rivers-Moore NA. 2014. Shifts in aquatic macroinvertebrate community structure in response to perenniality, southern Cape, South Africa. *Journal of Freshwater Ecology* 29(4): 475-490.

Eady BR, Rivers-Moore NA and Hill TR. 2013. Relationship between water temperature predictability and aquatic macroinvertebrate assemblages in two South African streams. *African Journal of Aquatic Science* 38(2): 163-174.

Ellender BR, Rivers-Moore NA, Coppinger CR, Bellingan TA and Weyl OLF. 2016. Towards using thermal stress thresholds to predict salmonid invasion potential. *Biological Invasions* 18: 3513-3525.

Ramulifho PA, Rivers-Moore NA, Dallas HF and Foord SH. 2018. A conceptual framework towards more holistic freshwater conservation planning through incorporation of stream connectivity and thermal vulnerability. *Journal of Hydrology* 556: 173-181.

Reizenberg JL, Bloy LE, Weyl OLF, Shelton JM and Dallas HF. 2019. Variation in thermal tolerances of native freshwater fishes in South Africa's Cape Fold Ecoregion: examining the east–west gradient in species' sensitivity to climate warming. *Journal of Fish Biology* 94(1): 103-112.

Rivers-Moore NA, Dallas HF and Morris C. 2013. Towards setting environmental water temperature guidelines: A South African example. Journal of Environmental Management 128: 380-392.

Rivers-Moore NA, Dallas HF and Ross-Gillespie V. 2013. Life history does matter in assessing potential ecological impacts of thermal changes on aquatic macroinvertebrates. *River Research and Application* 29(9): 1100-1109.

Rivers-Moore NA, Dallas HF, de Moor FC and Barendse J. 2018. Relationships of water temperature and aquatic macroinvertebrate community structure with non-native riparian plant densities in the southern Cape, South Africa. *African Journal of Aquatic Science* 43(3): 215-227.

Rivers-Moore NA, Ellender BR and Weyl OLF. 2019. Modelling expected trout ranges under current and future water temperature regimes in the Eastern Cape, South Africa. *African Journal of Aquatic Science* 44: 35-42.

Rivers-Moore NA, Hughes DA, Mantel S and Hill TR. 2008. First steps in the development of a water temperature model framework for refining the ecological Reserve in South African rivers. *Water SA* 34(5):1-12.

Rivers-Moore NA, Mantel S and Dallas HF. 2012. Prediction of water temperature metrics using spatial modelling in the Eastern and Western Cape, South Africa. *Water SA* 38: 167-176.

Rivers-Moore NA, Mantel S, Ramulifo P and Dallas HF. 2016. A disconnectivity index for improving choices in managing protected areas for rivers. *Aquatic conservation: Marine and Freshwater Ecosystems* 26: M29-38.

Rivers-Moore NA and Palmer R. 2018. The influence of turbidity and water temperature on black fly species in the middle and lower Orange River, South Africa. *Canadian Journal of Zoology* 96(6): 614-621.

Ross-Gillespie V, Picker MD, Dallas HF and Day JA. 2018. The role of temperature in egg development of three aquatic insects *Lestagella penicillata* (Ephemeroptera), *Aphanicercella scutata* (Plecoptera), *Chimarra ambulans* (Trichoptera) from South Africa. Journal of *Thermal Biology* 71: 158-170.

Shelton JM, Weyl OLF, Esler KJ, Paxton BR, Impson DN and Dallas HF. 2018. Temperature mediates the impact of non-native rainbow trout on native freshwater fishes in South Africa's Cape Fold Ecoregion. *Biological Invasions* 20(10): 2927–2944.

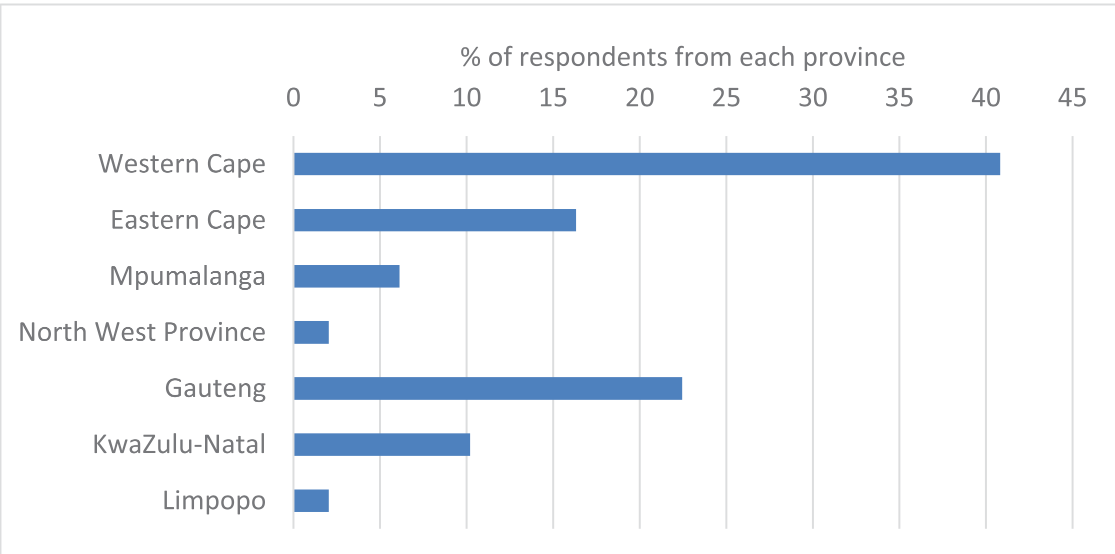
Shelton JM, Weyl OLF, Chakona A, Ellender BR, Esler KJ, Impson DN, Jordaan MS, Marr SM, Ngobela T, Paxton BR, Van der Walt JA and Dallas HF. 2017. Vulnerability of Cape Floristic Region freshwater fishes to climate change and other human impacts. *Aquatic Conservation* 28(1): 68-77.

Appendix 3 Summary of questionnaire results

The following section provides an overview of the results of the questionnaire distributed to 97 river managers and practitioners across South Africa. A total of 49 individuals responded, a rate of 50.5%. The respondents, their organisation and province are tabulated and the relative proportion of respondents by province summarised graphically.

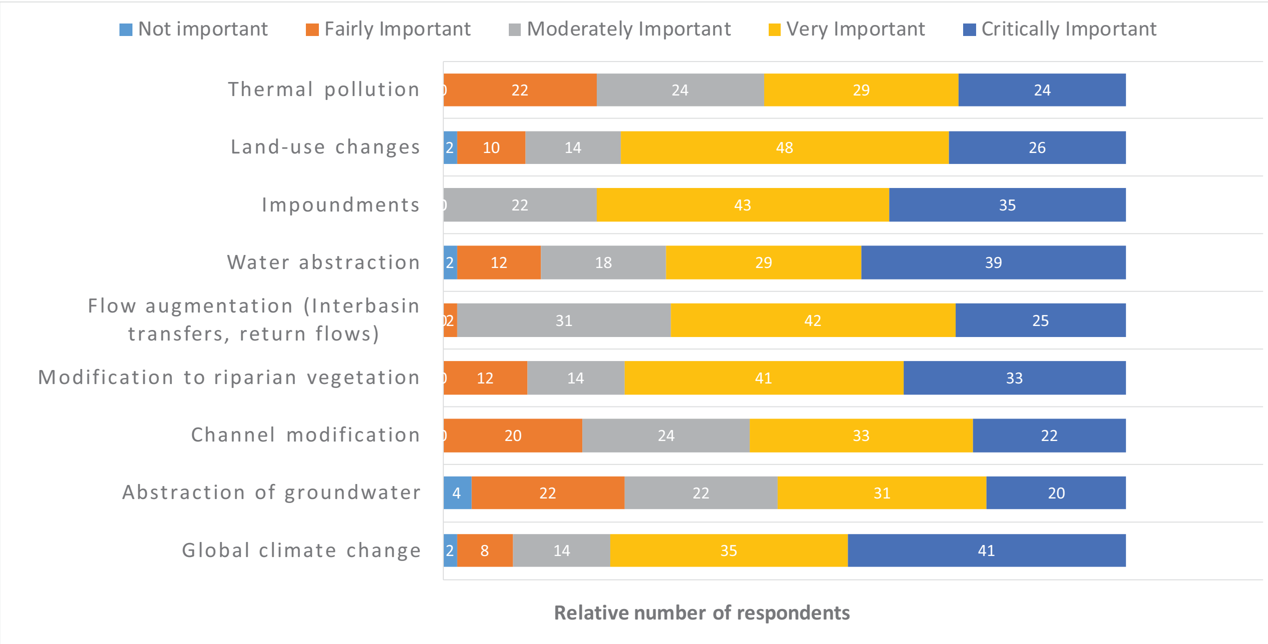
Participants	Organisation	Province
Andrew Gordon	Department of Water and Sanitation	Western Cape
Anton Bok	Anton Bok Aquatic Consultants cc	Eastern Cape
Bentley Engelbrecht	Department of Water and Sanitation	Western Cape
Bruce Paxton	Freshwater Research Centre	Western Cape
Chris Dickens	International Water Management Institute	Gauteng
Christa Thirion	Department of Water and Sanitation	Gauteng
Colleen Todd	Independent Consultant	Gauteng
Dean Impson	CapeNature	Western Cape
Dean Ollis	Freshwater Consulting Group	Western Cape
Denise M Schael	Nelson Mandela University	Eastern Cape
Dirk Roux	South African National Parks	Western Cape
Estelle van Niekerk	AECOM	Gauteng
Ferdie de Moor	Albany Museum	Eastern Cape
Freek Venter	South African National Parks	Mpumalanga
Gerhard Diedericks	Environmental Biomonitoring Services	Mpumalanga
Gordon O'Brien	University of KwaZulu-Natal	KwaZulu-Natal
Heather Louise Malan	Freshwater Research Centre	South Africa
Helen Barber-James	Albany Museum	Eastern Cape
Ian Bailey	Umgeni Water	KwaZulu-Natal
Ian Bredin	Institute for Natural Resources	KwaZulu-Natal
Jeanne Gouws	CapeNature	Western Cape
Jenny Day	University of Cape Town/University of the Western Cape	Western Cape
Jeremy Shelton	Freshwater Research Centre	Western Cape
Justine Ewart-Smith	Freshwater Research Centre	Western Cape
Karl Reinecke	Southern Waters	Western Cape
Kate Snaddon	Freshwater Consulting Group	Western Cape
Kwazi Majola	Department of Water and Sanitation	Gauteng
Leo Quayle	Institute of Natural Resources	KwaZulu-Natal
Mark Rountree	Fluvius Environmental Consultants	Western Cape

Participants	Organisation	Province
Mike Silberbauer	Department of Water and Sanitation	Gauteng
Neels Kleynhans	Department of Water and Sanitation	Gauteng
Nelson Odume	Rhodes University	Eastern Cape
Nico Rossouw	Aurecon	Western Cape
Patsy Scherman	Scherman Environmental	Eastern Cape
Peter Kimberg	The Biodiversity Company	Gauteng
Renelle Pillay	Pongola to Umzimkulu Proto CMA	KwaZulu-Natal
Rob Palmer	Nepid Consultants CC	Mpumalanga
Robert Siebritz	City of Cape Town	Western Cape
Ruth-Mary Fisher	South African National Parks	Western Cape
Shaddai Daniel	Department of Water and Sanitation	Western Cape
Sukhmani Mantel	Rhodes University, Institute for Water Research	Eastern Cape
Thulani Matyeni	Department of Water and Sanitation	Eastern Cape
Toni Belcher	Blue Science	Western Cape
Tovhowani Nyamande	Department of Water and Sanitation	Gauteng
Victor Wepener	North-West University	North West Province
Warren Aken	Golder Associates	Gauteng
Wietsche Roets	Department of Water and Sanitation	Gauteng
Wynand Vlok	BioAssets	Limpopo

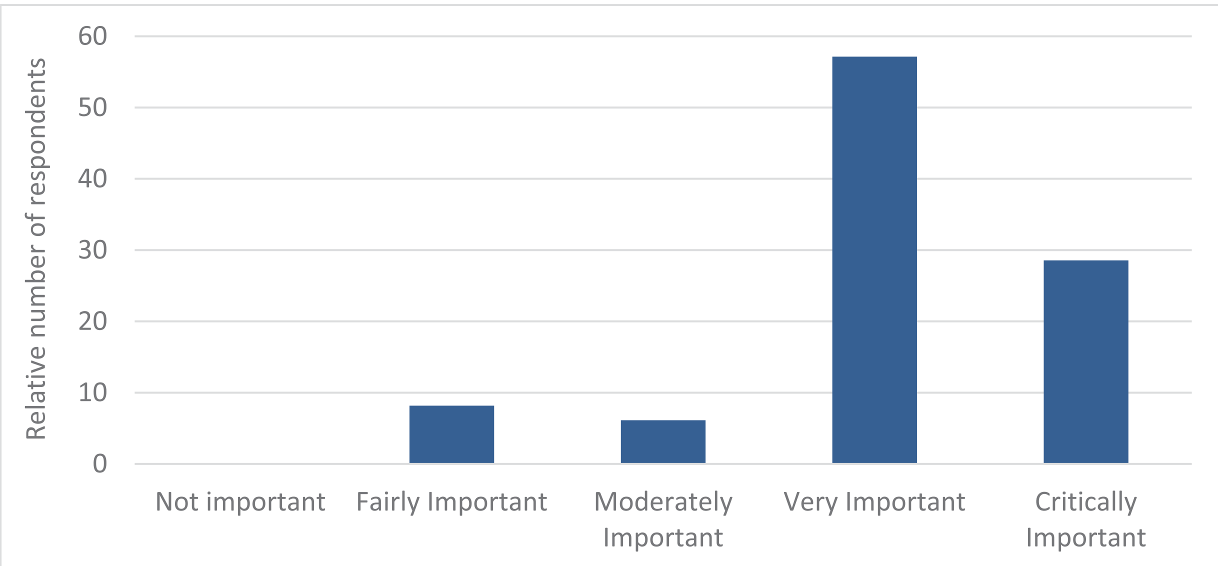


Questions

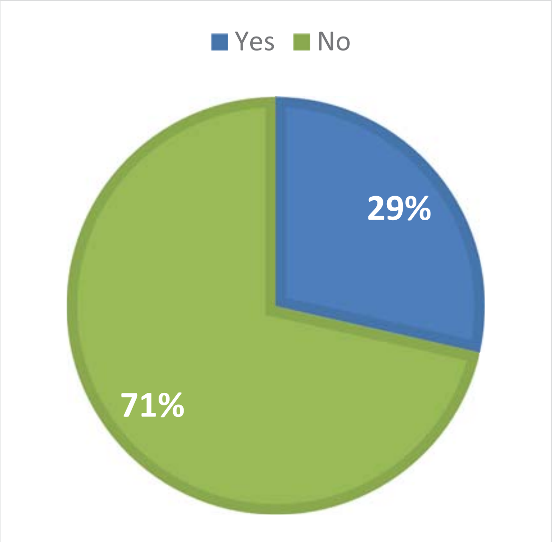
On a scale of 1 to 5 (1 = Not important; 5 = Critically important), please indicate which thermal impacts you consider important in the South African context



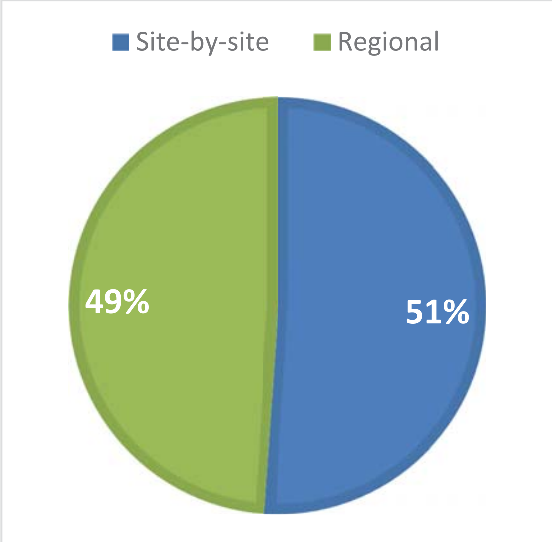
On a scale of 1 to 5 (1 = Not important; 5 = Critically important), please indicate how important it is to include water temperature in ecological Reserve studies



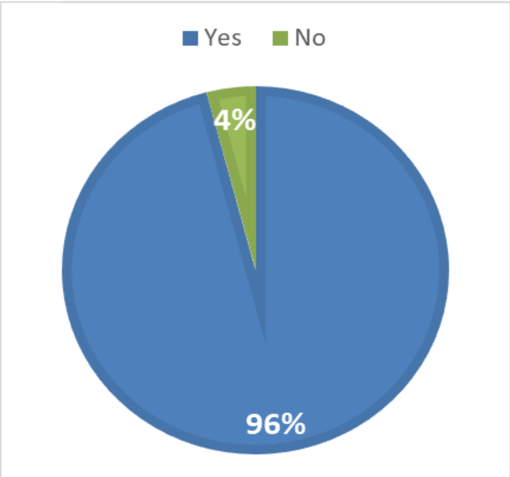
Have you previously included water temperature in ecological Reserve studies?

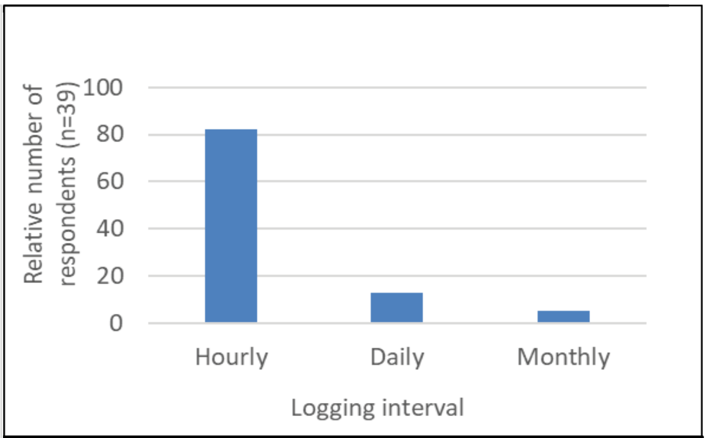


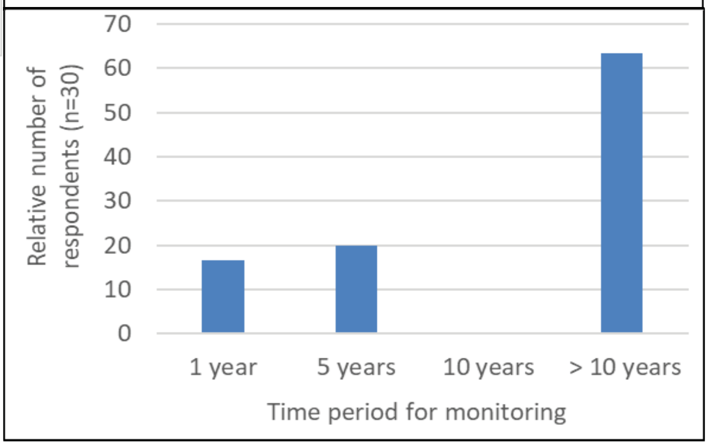
Would your preference be for environmental water temperature guidelines to be defined on a site-by-site basis, or using a regional approach that includes statistical confidence levels?



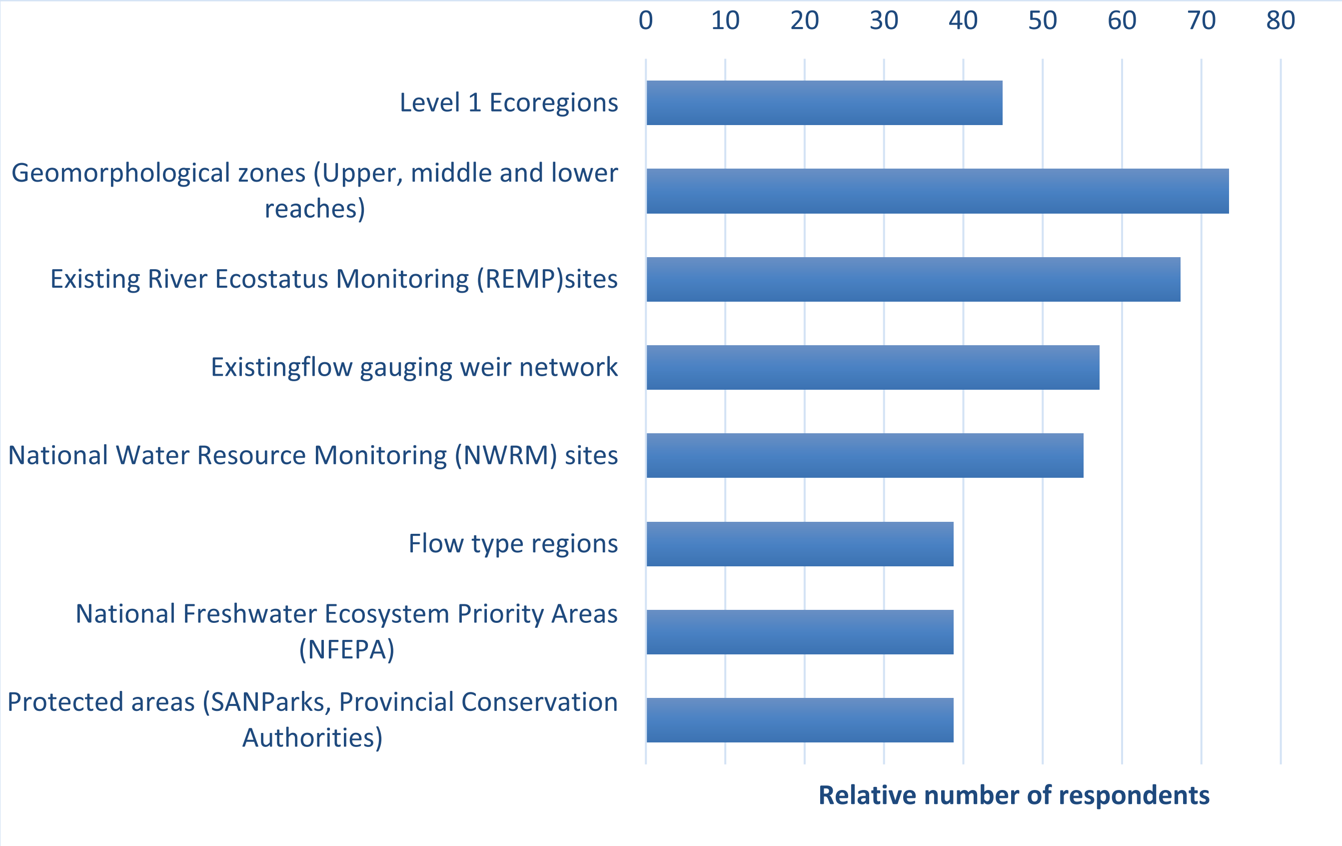
Do you consider it important for water temperature to be routinely monitored?



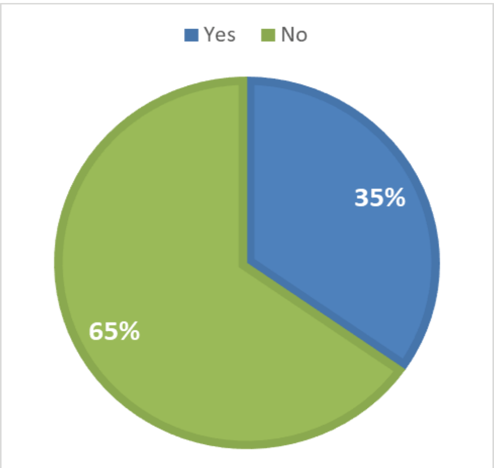




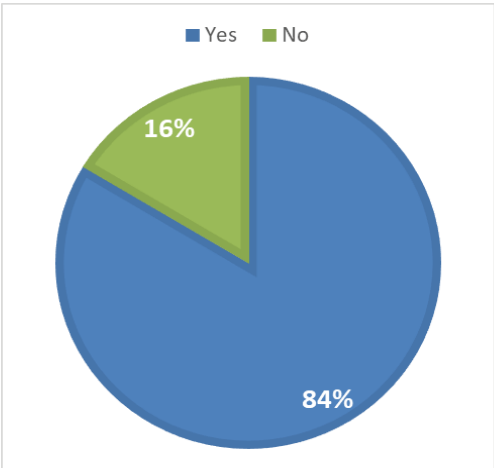
If YES, which of the following should be considered when selecting water temperature monitoring sites?



Do you or your organisation currently monitor water temperature using loggers?



Would you or your organisation be open to collaborating on the design and implementation of a water temperature monitoring network (including taking responsibility for routine downloading of water temperature data for uploading to a central database)?



Appendix 4 Participants in the user requirement workshops

User requirements workshop: Cape Town Workshop

Name	Affiliation	Presentation
Andrew Gordon	DWS	
B. Mabovu	DWS	
Bentley Engelbrecht	DWS	
Bruce Paxton	FRC	
Dean Impson*	Cape Nature	
Dean Ollis	Freshwater Consulting Group	
F. Rhoda	DWS	
Heather Malan	FRC	
Helen Dallas	FRC	Proposed approach to incorporating water temperature into the ecological Reserve
Jeanne Gouws	Cape Nature	
Justine Ewart-Smith	Freshwater Consulting Group	
Martine Jordaan	Cape Nature	
N. Ndobeni	DWS	
N. Veruaaic	DWS	
Nick Rivers-Moore	FRC	History of water temperature in the Reserve
Nico Rossouw*	Aurecon	An overview of developments with respect to incorporating water temperature in the Reserve (ppt and voice over)
Rembu Magoba	City of Cape Town	
Shaddai Daniel	DWS	
Thembela Bushula	DWS	
Toni Olsen	FRC	
Tumisho Ngobela	Freshwater Consulting Group	
Warren Dreyer	DWS	

* unable to attend, apologies sent

User requirements workshop: Pretoria Workshop

Name	Affiliation	
Barbara Weston	DWS	
Bonani Madikizela*	Water Research Commission	
Chris Dickens*	International Water Management Institute	
Christa Thirion	DWS	
Colleen Todd	Independent	
Francois Retief*	North West University	
Helen Dallas	FRC	
Jackie Jay*	DWS	
Tichatonga Gonah	DWS	
Harold van Niekerk	DWS	
Neels Kleynhans*	DWS	
Nick Rivers-Moore	FRC	Proposed approach to incorporating water temperature into the ecological Reserve
Patsy Scherman*	Scherman Environmental	
Pieter Viljoen	DWS (Water Resource Planning Systems)	An overview of South Africa's water quality management policies and strategies, including the history of the RQO/Policy framework's development.
Sebastian Jooste	DWS	Water quality: ecological Reserve, Water Resource Classification + RQOs
Tovhowani Nyamandi	DWS	
Victor Wepenaar*	North West University	
Wynand Malherbe	North West University	Outlined the master's and short-term Learning Programmes in Environmental Water Requirements being offered by the North-West University
Yakeen Atwaru	DWS	

* unable to attend, apologies sent

Appendix 5 Participants in the knowledge dissemination workshops

Knowledge dissemination workshop: Cape Town Workshop

Name	Organisation
Aneri Swanepoel	FRC
Bentley Engelbrecht*	DWS
Brandon Wynne	City of Cape Town
Bruce Paxton	FRC
Dean Impson*	Cape Nature
Dean Ollis*	Freshwater Consulting Group
Duke Jephtha	DWS
Dulce Lazana	Aurecon
Felicia Magutywa	City of Cape Town
Heather Malan*	Independent
Helen Dallas	FRC
Jeanne Gouws	CapeNature
Justine Ewart-Smith*	Freshwater Consulting Group
Kate Snaddon	FRC
Linda Rossouw	Environmental and Water Quality Consultant
Lungiswa Mgxwati	DWS
M. Tshikalange	DWS
Makhesh Mik	DWS
Martine Jordaan	CapeNature
Maukisi Noqhamza	DWS
Melandri Rafferty	FRC
Mtandana Sherline	DWS
Nick Rivers-Moore	FRC
Nico Rossouw	Aurecon
Nicosinathi Mkonto	DWS
Philip Frenzel	FRC
Pumza Buwa	DWS
Rassie Nieuwoudt*	DWS
Rembu Magoba*	City of Cape Town
Robert Siebritz	City of Cape Town
Shaddai Daniel*	DWS
Melissa Lintnaar-Strauss	DWS: Resource Protection
Toni Olsen	FRC
Torch Thembisa*	DWS
Tshilidzi Manauhela	DWS
Warren Dreyer	DWS

* unable to attend, apologies sent

Knowledge dissemination workshop: Pretoria Workshop

Name	Organisation
Adaora Okonkwo	DWS: Head Office
Barbara Weston*	DWS
Bashan Govender*	DWS
Bonani Madikizela*	Water Research Commission
Bongizeuzo Nyawo	DWS: Information Programmes
Boniwe Nobubele	DWS: Head Office
Caroline Tlowana*	DWS
Christa Thirion	DWS: Resource Quality Information Services
Colleen Todd*	DWS
Elna Vermark*	DWS
Helen Dallas	FRC
Henry Maluleke	DWS: Reserve Determinations
Jackie Jay*	DWS
Joyce Machaba*	DWS
Koleka Makanda	DWS
Kwazikwakhe Majola	DWS: Reserve Determinations
Lebo Mosoa*	DWS
Lerato Molokomme	DWS: Head Office
Luwenle Mulengaphuma	DWS: Water Resource Classification
Malegodi Mahlatji	DWS: Resource Protection & Waste
Marcus Selepe*	DWS
Mbiza Noloyiso	DWS: Resource Quality Information Services
Mike Silberbauer	DWS: Resource Quality Information Services
Mkhevu Mnisi	DWS: Water Resource Classification
Ndiyhuwo Netshiendeulu	DWS: Reserve Determinations
Nick Rivers-Moore	FRC
Nobubele Boniwe	DWS: Head Office
Patsy Scherman*	Scherman Environmental
Philani Khoza	DWS: Reserve Determinations
Pumza Dubula	DWS: Climate Change
Rendani Mudzanani	DWS: Reserve Determinations
Sazi Mthembu	DWS: Resource Quality Information Services
Sebastian Jooste*	DWS
Stanley Nzama	DWS: Reserve Determinations
Tichatonga Gonah	DWS: Reserve Determinations
Tinylko Weswiswi	DWS: Reserve Determinations
Tovhowani Nyamande	DWS: Source Directed Control
Yakeen Atwaru	DWS: Head Office

* unable to attend, apologies sent