ENVIRONMENTAL WATER TEMPERATURE GUIDELINES FOR PERENNIAL RIVERS IN SOUTH AFRICA.

HF DALLAS AND NA RIVERS-MOORE

VOLUME 2: A TECHNICAL MANUAL FOR SETTING WATER TEMPERATURE TARGETS

WATER RESEARCH COMMISSION

TT 799/2/19

Environmental water temperature guidelines for perennial rivers in South Africa. Volume 2: A technical manual for setting water temperature targets

Report to the
WATER RESEARCH COMMISSION
by

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The publication of this report emanates from a project entitled Environmental water temperature guidelines: bridging the gap between research and implementation (WRC Project No K5/2537).

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 1: Technical Report. Water Research Commission Report No. TT 799/1/19, 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.

Cover photograph: Rooielskloof River, Western Cape, South Africa. Jeremy Shelton.

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Introduction

This 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 (see Box 1); and Source Directed Controls for perennial rivers in South Africa. It speaks directly to several tools, packaged into a **toolbox**, developed for establishing environmental water temperature guidelines.

It 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 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, for example, submitted a water use licence application (Figure 1).

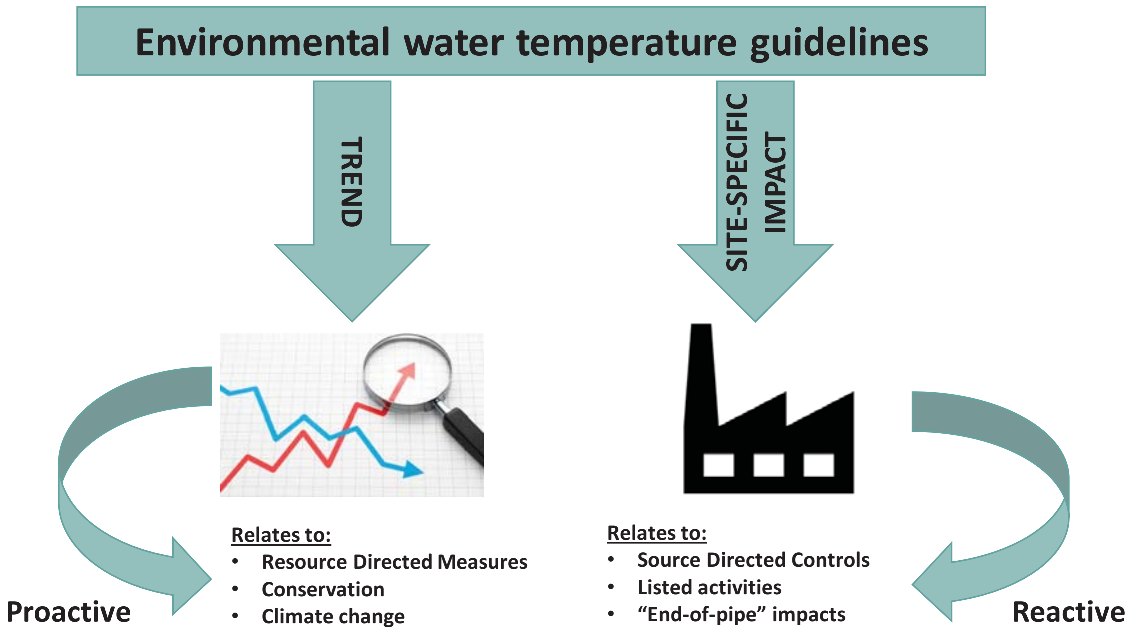


Figure 1. Environmental water temperature guidelines for site-specific impacts and trend analyses

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 a predetermined condition (Table 1) in response to factors such as global climate change and water abstraction.

Table 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

Impacts thus have spatial and temporal aspects for mitigation; these relate to a thermograph remaining within an annual reference envelope (temporal), and reference conditions having been re-established within a defined downstream distance of the impact source. Thermal reset distance is linked to discharge volumes, which enable downstream distances to be set for normalisation of thermal impacts based on stream order and site flow volumes (Palmer and O'Keeffe 1989).

BOX 1: THE ECOLOGICAL RESERVE & RESOURCE QUALITY OBJECTIVES

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 objectives for monitoring 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, stable and healthy riparian vegetation, and which supports basic human needs.

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.

Water temperature in rivers

Southern Africa has been identified as a 'critical region' of water stress and existing anthropogenic stresses on freshwater ecosystems are substantial. Water temperature, together with flow, are master variables 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 temperatures in a river are final values resulting from a number of complex assimilated physical processes (Table 2). 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. 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

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 3. Further detail on each impact, their prevalence in South African rivers and mitigation options are provided in **Appendix 1**. The effects of temperature changes on physico-chemical parameters (water quality) are provided in **Appendix 2**.

Table 3. 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

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 4). The effects and the response of each variable in relation to temperature are further described in **Appendix 3**.

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

- **Screening Process** (Figure 2), and
- **Evaluation Process**, which includes two components:
  - Establishing Reference Indicators of Thermal Alteration (thermal metrics) and a Reference Thermograph (Figure 7), and
  - Evaluating deviation from Reference thermal metrics and a Reference Thermograph (Figure 8).

Information needed to do the screening and evaluation processes will ultimately be provided through the Freshwater Biodiversity Information System (FBIS) (www.freshwaterbiodiversity.org).

Table 4. 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

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 (Figure 2). Two examples of the screening process are described in Boxes 2 and 3.

When should water temperature be considered?

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

1) **How resilient is the site, reach or river to changes in water temperature? =** Evaluating system resilience

Aspects to consider include:

- What is the stream order?
- What geomorphological zone is the site in?
- Is the site, reach, river ground- or surface-water dependent?
- What is the water yield?
- How transformed is the catchment?

These factors have been integrated into a Map of Thermal Resilience and Resilience radar plots, based on quinary level data.

2) **Are there other hydrological, physico-chemical (water quality) and habitat considerations that could magnify or diminish thermal impacts?**

- Is the flow natural or transformed?
- Is there an impoundment upstream or at the site?
- Are there physico-chemical (water quality) issues that will be exacerbated when heated by water?
- Is there potential for algal blooms or invasive aquatic weeds to dominate?
- Is the activity likely to affect the character and condition of the instream and riparian habitat, and sediment processes?

Naturalised and present-day flows per Water Management Area (WR 2012) are provided. Department of Water and Sanitation hydrological and water quality gauging stations are indicated.

3) **How sensitive are the river organisms?**

Aspects to consider include:

- Is the site in a protected area, Critical Biodiversity Area, Freshwater Ecosystem Priority Areas, important fish area, etc?
- What is the Present Ecological State, Ecological Importance and Ecological Sensitivity of the site?
- Is the site in an A or B Ecological Category based on SASS?
- Are there endemic species?
- Are there IUCN Red List species present?
- Are there species with specific thermal requirements?
- Are there species with specific oxygen requirements?

Available data are provided.

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 would be screened at the river-scale.

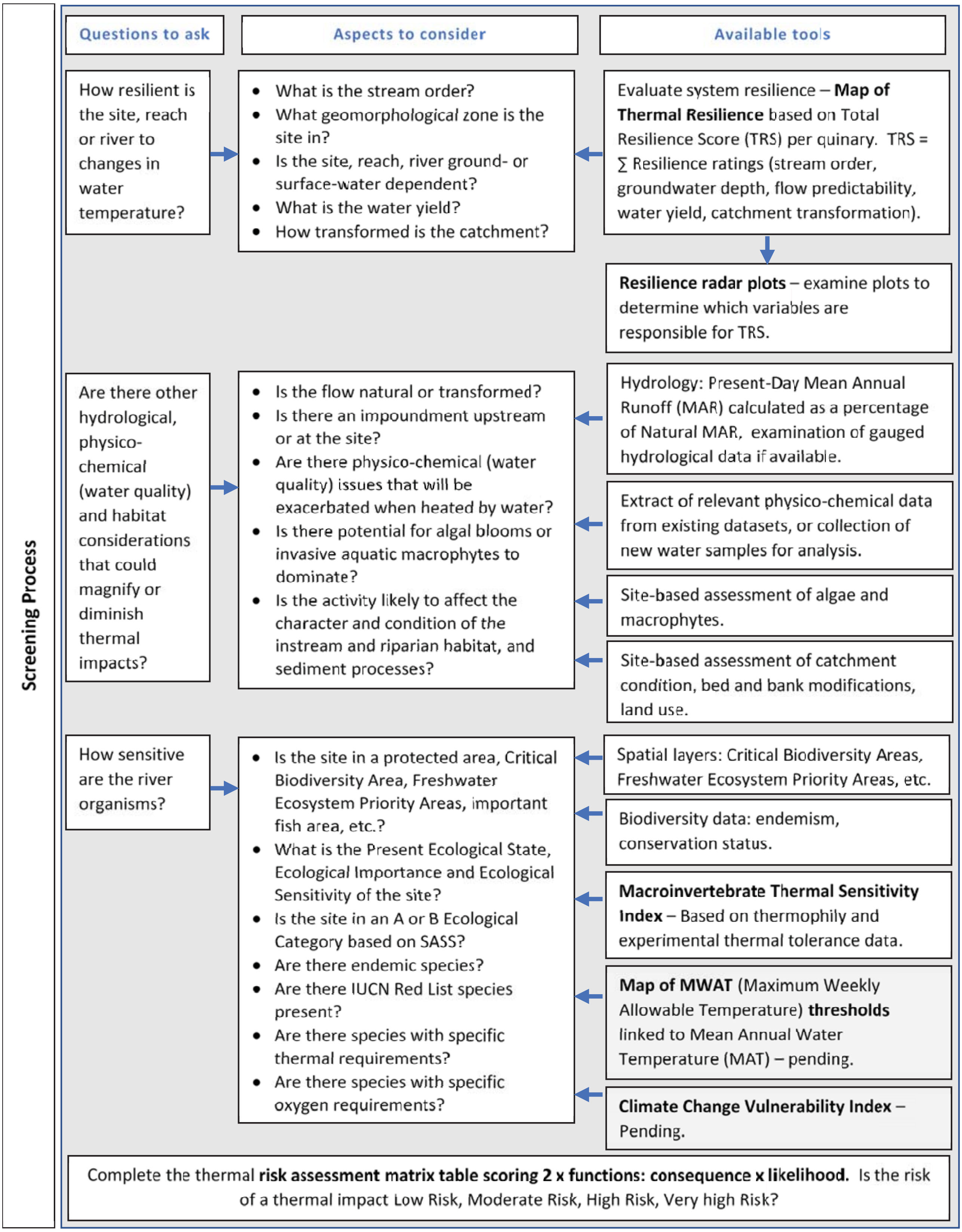


Figure 2. Work flow diagram for the Screening Process for managing water temperature in rivers

Evaluating system resilience

System resilience refers to a river's ability to withstand external impacts to a greater or lesser degree. 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. Note that the resilience specifically refers to the river or system's resilience and not to the resilience of the biota, which may have adapted to, for example, surface-fed rivers, and/or with unpredictable flow.

A database of variables likely to indicate system (river) resilience to thermal stress has been developed for all quinary catchments (Table 5). Quinary catchments are sub-quaternary catchments defined by natural breaks in topographic homogeneity (Schulze et al. 2011). For example, higher-order streams (6 and 7 order) are more resilient to thermal stress compared to first- and second-order streams. Similarly, a site with more groundwater input is likely to be more resilient than a site with less groundwater input, because of the buffering effect of groundwater on water temperature variability. 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 (Figure 3). This map allows users to evaluate if the site, reach or river is likely to be resilient or vulnerable to thermal stress based on five catchment variables. The user is then able to further explore which variables are responsible for this resilience rating by examining radar plots, where those variables responsible for system resilience or vulnerability are unpacked (Figure 4). In Figure 4, the site represented by the blue line has high resilience, while the site representented by the red line has low resilience.

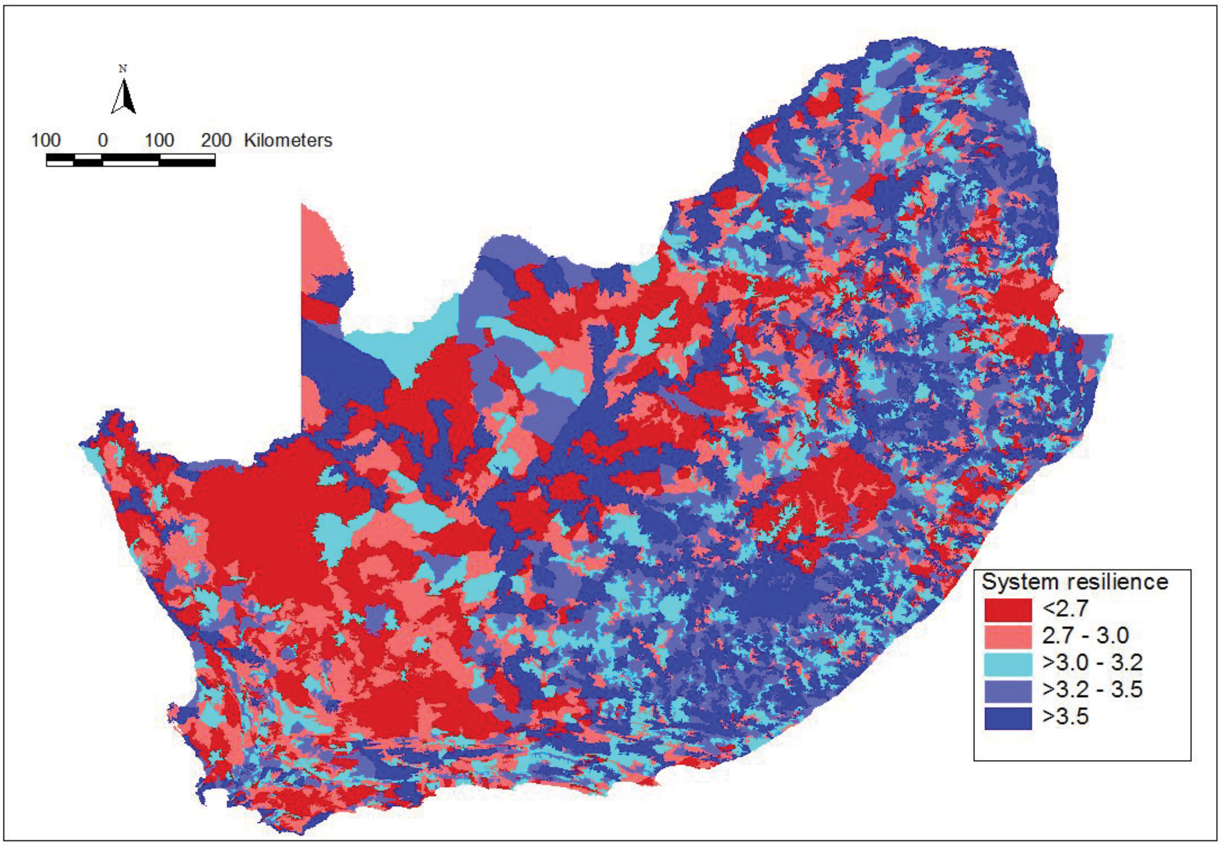


Figure 3. Map of Thermal Resilience based on calculation of Total Resilience Score for each quinary catchment (low resilience = red; high resilience = blue)

Table 5. Variables associated with quinary catchments for generating automated radar plots to assist in inferring system resilience. Details of the source of the data and the method used are provided. An explanation of system resilience is given for each.

Variable	Source Data	Method	System Resilience (1 = greatest resilience; 0 = least resilience)
Stream order	DWS 1:500 000 rivers coverage	Each quinary catchment was assigned a stream order through a process of iteratively selecting all catchments intersected with stream order lines, beginning with stream order 1 and ending with stream order 7.	Larger rivers (higher-order streams) are more resilient to thermal stress compared to smaller streams and rivers (first- and second-order).
Groundwater depth	Colvin et al. (2007)	The mean groundwater depth was calculated for each quinary catchment using raster images Colvin et al. (2007).	Rivers with shallow groundwater depths are more likely to have groundwater inflow (i.e. thermal buffering) and thus greater resilience to thermal stress compared to rivers with deep groundwater.
Flow predictability	Rivers-Moore et al. (2016)	Generated using simulated natural flow time series (Schulze et al. 2011) using the Indicators of Hydrological Alteration software (Richter et al. 1996).	Systems with high predictability (towards 1) have higher numbers of sensitive species and are more vulnerable to thermal disruption. Such systems have higher resilience because diverse biotic communities help to stabilize river systems (Vannote et al. 1980).
Water yield	Schulze et al. (1997)	Calculated from national grids of monthly median precipitation and monthly A-pan evaporation. Water yield is based on monthly precipitation minus evaporation, as per the method of Rivers-Moore et al. (2007). Values are rescaled to values from 0-1 based on the monthly minimum value.	Catchments with high rainfall and low evaporation will be more resilient to thermal stress compared to rivers with low rainfall and high evaporation.
Catchment transformation	Geoterraimage (GTI 2015)	The 72 land cover classes in the 30x30m resolution land cover image, were reclassified into two classes (natural versus non-natural). The percentage natural land cover for each quinary catchment was calculated from this.	Catchments with a greater percentage of natural vegetation are likely to be more resilient to thermal stress compared to highly transformed catchments.

Given that resilience ratings are generated per quinary catchment, it is possible that there is a degree of inaccuracy for quinary catchments that contain rivers of, for example, different stream orders. The user will thus be able to override the default values for a quinary with higher accuracy data if available.

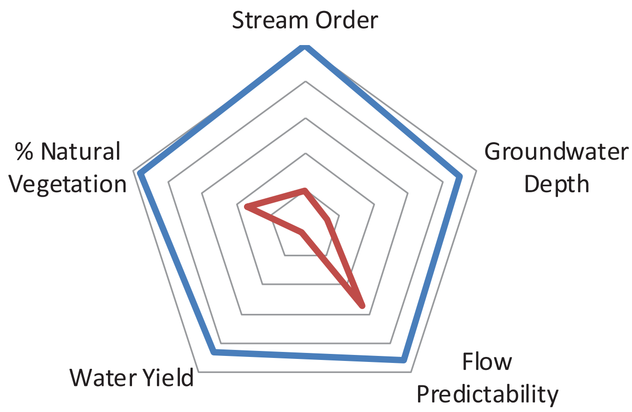


Figure 4. Radar plot showing the relative importance of five site variables potentially affecting system resilience. The blue line represents a site with high resilience, while the red line represents a site with low resilience.

Here are some typical examples:

- Lower-order streams, especially mountain streams, are likely to have more predictable water temperature regimes, and higher numbers of thermally sensitive species.
- Higher-order streams are likely to exhibit higher daily thermal ranges and have more generalist species.
- Rivers with higher volumes of water will be more resilient to thermal pollution.
- Groundwater abstraction will increase the vulnerability of rivers to climate change impacts.
- Catchments with a high precipitation: evaporation ratio are likely to be less thermally stressed.
- The discharge of heated effluent may exacerbate the toxicity of the effluent as the toxicity of chemicals may be significantly increased when released in association with elevated temperatures.
- Removal of riparian vegetation has a greater impact on water temperature in lower-order streams (1^{st} and 2^{nd}) compared to higher-order rivers (5^{th}).

Hydrological, physico-chemical and habitat considerations

The practitioner needs to examine aspects related to hydrology, physico-chemistry (water quality) and habitat (geomorphological and riparian condition). Various data will be automated within FBIS.

- Hydrology: Naturalised and present-day flows, expressed as monthly flows in million cubic metres per month, per Water Management Area (WR 2012). Naturalised flows are as for WR 2012 from 1920 to 2009 (hydrological years). Naturalised flow was obtained by removing man-made influences such as dams, irrigation schemes, abstractions for mines, industry and towns, return flows from treatment works, etc. Naturalised flows are used in other models such as the Water Resources Yield Model, Water Quality Model, Hughes Desktop Reserve Model (for Ecological Water Requirements), Water Resources Planning

Model, etc Present day flow is the streamflow with all land use set to 2009 hydrological year levels, and includes afforestation, alien vegetation, paved areas, abstractions, return flows and transfers. Hydrological data from Department of Water and Sanitation gauging stations should be examined if available.

- Physico-chemistry (water quality): Data from Department of Water and Sanitation if available. Parameters of concern include dissolved oxygen concentration, turbidity, inorganic nitrogen concentration, inorganic phosphorus concentration, un-ionised ammonia (NH_3) concentration, chemicals such as atrazine, cadmium, cyanide, fluoride, lead, phenol, selenium, xylene and zinc. The practitioner needs to evaluate each of these parameters, specifically if they are likely to be exacerbated with an increase or decrease in water temperature. The potential for algal blooms or invasive aquatic macrophytes to dominate also needs to be evaluated.
- Habitat (geomorphology and riparian): An assessment should be undertaken on the condition of instream habitat and riparian habitats, and the effect on sediment processes.

Sensitivity of river organisms

The practitioner needs to establish if the site is in a protected area, Critical Biodiversity Area, Freshwater Ecosystem Priority Area, important fish area, etc. The following information will ultimately be generated in FBIS to assist with establishing if sensitive species are present at the site.

- Indication if the site is in a Protected area, Critical Biodiversity Area, Freshwater Ecosystem Priority Area, important fish area.
- Present Ecological State, Ecological Importance and Ecological Sensitivity will be provided based on available desktop PESEIS assessments (Department of Water and Sanitation 2014).
- Ecological Category based on aquatic invertebrate SASS (South African Scoring System) data and existing data interpretation guidelines of Dallas (2007).
- Endemic species based on species distributions as follows:
    - Widespread (more than one Freshwater Ecoregion)
    - Regional endemic level 1 (endemic to a Freshwater Ecoregion - e.g. Cape Fold Ecoregion, more than one primary catchment)
    - Regional endemic level 2 (endemic to one primary catchment)
    - Micro-endemic level 1 (< 5 rivers, within one primary catchment)
    - Micro-endemic level 2 (1 river)
- IUCN Red List species present, based on conservation status as listed on the IUCN website.
- Species with specific thermal requirements. A prototype Thermal Sensitivity Index based on aquatic macroinvertebrates has been developed. Here we assigned each SASS taxon a Thermal Sensitivity Weighting based on a combination of an estimate of thermophily (Chessman 2012) and thermal limits (Dallas and Rivers-Moore 2012, Dallas, unpublished data). Thermophily is a product of the mean instantaneous temperature associated with samples in which that taxon was detected, divided by mean water temperature of all samples (Chessman, 2012). As with SASS, the Thermal Sensitivity Weightings of all the taxa recorded at a site are summed to derive a Thermal Sensitivity Score for a site, based on the taxa sampled. The Average Thermal Sensitivity Per Taxon is then generated by dividing Thermal

Sensitivity Score by the number of taxa. The relative proportion of highly thermally sensitive, moderately thermally sensitive, moderately thermally tolerant, and highly thermally tolerant is generated (Figure 5).

- Species with specific oxygen requirements. To date, dissolved oxygen requirements for species is very limited, although research is underway on some fish species in the Western Cape. Some data exist on air-breathing aquatic invertebrates versus non-air-breathing ones.

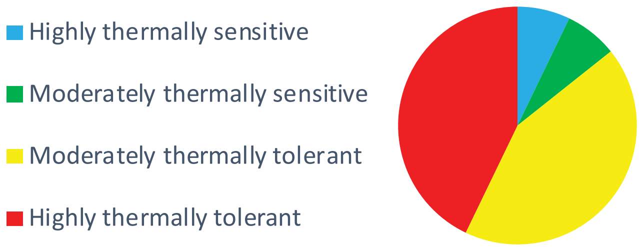


Figure 5. Pie diagram showing the relative proportion of aquatic macroinvertebrates in each thermal class.

Quantifying thermal stress and assessing risk

Thermal impacts are best understood in terms of risk. The assessment of thermal stress in terms of risk forms the final stage of the screening process. Calculation of risk needs to be undertaken by water resource practitioners when evaluating thermal impacts at a specific site. Some thermal impacts are likely to have a more significant impact at specific sites, reaches or rivers, and site-specific conditions must be considered when calculating risk. The data generated during the screening process is used to evaluate risk of thermal impact(s) at a site. Where more than one thermal impact is present at a site, then the potential synergistic and antagonistic interactions should also be considered.

A useful approach is to generate a risk rating for each thermal impact at a site using a thermal risk assessment matrix (**Appendix 4**). The aspects covered in the screening process are aggregated into the risk assessment matrix and are described below. For each aspect a rate from 1 to 5 is either auto-calculated or selected by the user. **Appendix 1** and **Appendix 2** can assist in this task. The process for evaluating thermal impacts at a site includes the following steps:

1. Thermal impact(s) at the site are identified (or potential impact in the case of, for example, an application for a water use licence),
2. **System resilience** is auto-calculated based on Total Resilience Score linked to one of five rating categories (1= Very high resilience, 2= High resilience, 3= Medium resilience, 4= Low resilience and 5= Very low resilience).
3. The **severity** of the thermal impact on the resource quality is rated for hydrology, physico-chemistry (water quality), habitat and biota.
   i. **Hydrology**: The severity of the impact of the activity on the flow regime is scored based on flow sub-categories expressing the Present-Day Mean Annual Runoff (MAR) as a percentage of Natural MAR per Water Management Area. If more accurate hydrological data are available then these should be used in preference to the % MAR per Water Management Area.

ii. **Physico-chemistry (water quality)**: Score the impact of the activity based on physico-chemical sub-categories, including: dissolved oxygen concentration, turbidity, average inorganic nitrogen concentration, average inorganic phosphorus concentration, un-ionised ammonia (NH_3) concentration, other chemicals present (cadmium, zinc and lead, atrazine, cyanide, fluoride, phenol, selenium and xylene), potential for algal blooms, and potential for growth of invasive aquatic macrophytes.

iii. **Habitat (Geomorphology + Vegetation)**: Score the impact of activity on the character and condition of the instream and riparian habitat, and sediment processes.

iv. **Biota**: The impact of the activity on the biota is rated by assessing the sensitivity of aquatic biota and conservation importance of the site. It is auto-calculated based on the following biota sub-categories: protection of the site, Present Ecological State Category, Mean Ecological Importance Class, Mean Ecological Sensitivity Class, Ecological Category (SASS only), presence of endemic species, IUCN Red List species, thermally sensitive taxa, and taxa sensitivity to low dissolved oxygen.

Overall severity is then calculated as the average of severity scores given for hydrology, physico-chemistry, habitat and biota.

4. The **spatial scale** of the activity and **duration** of the activity are then rated.
5. The **consequence** of the activity is then calculated as **Consequence = (∑ Resilience + Severity + Spatial scale + Duration)/4**.
6. The **likelihood** of each activity at the site is then rated based on the frequency of activity and the frequency of the impact such that **Likelihood = (∑ frequency of activity + frequency of the impact)/2**.
7. The **Risk Rating** is then generated based on predetermined Risk Classes: Low Risk (≤ 5), Moderate Risk (6-10), High Risk (11-16), Very high Risk (> 16) (Figure 6).

Consequence	Very unlikely	Not likely	Likely	Very Likely	Extremely likely
Extreme	5	10	15	20	25
Severe	4	8	12	16	20
Substantial	3	6	9	12	15
Moderate	2	4	6	8	10
Slight	1	2	3	4	5

Likelihood

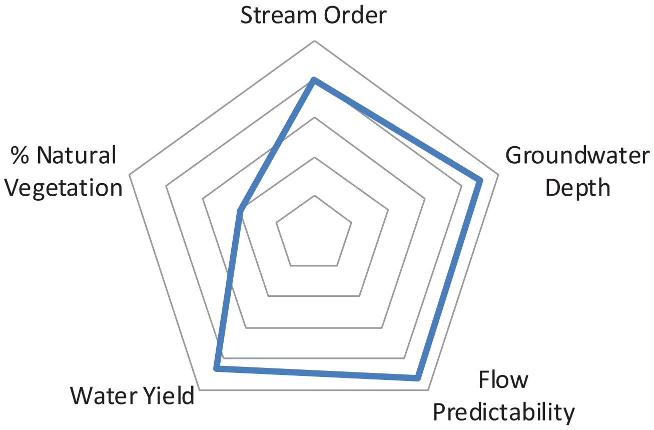
- Very high risk
- High risk
- Moderate risk
- Low risk

Figure 6. A risk evaluation matrix table scoring 2 x functions: consequence x likelihood, where consequence is the Sum of Resilience + Severity + Spatial Scale + Duration); and likelihood is the sum of Frequency of the activity + Frequency of Impact.

BOX 2: Screening Process - Example 1

Treated wastewater is discharged into a lowland river that is already heavily impacted by cumulative impacts, including urban runoff, agricultural return flows and water abstraction. The discharged water is heated, as the water received for treatment is heated.

System Resilience: Total Resilience Score = 3.88

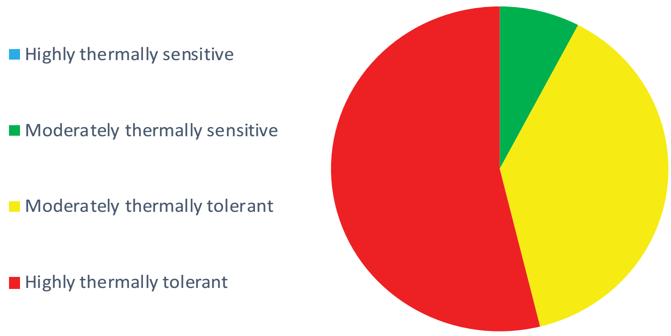


Hydrological, physico-chemical and habitat considerations:

Hydrology	
Naturalized streamflow per Water Management Area	571 million m^3/a
Present Day streamflow per Water Management Area	220 million m^3/a
Present Day Mean Annual Runoff (MAR) as a percentage of Natural MAR	38.5%
Physico-chemistry (water quality)	
Dissolved oxygen concentration	< 5.0 mg/ℓ
Turbidity	Opaque
Average inorganic nitrogen concentration	1.5 mg/ℓ (Mesotrophic)
Average inorganic phosphorus concentration	0.01 mg/ℓ (Mesotrophic)
Un-ionised ammonia (NH_3) concentration	0.015 mg/ℓ
Other chemicals present	Unknown
Potential for algal blooms	No
Potential for growth of invasive aquatic macrophytes	No
Habitat (geomorphology and riparian)	
Condition of instream habitat	Low
Condition of riparian habitat	Low
Effect on sediment processes	Low

Sensitivity of river organisms:

Protected area	No
Critical biodiversity areas	No
Ecological support areas	No
NFEPA fish sanctuaries	No
National Freshwater Ecosystem Priority Area	No
Present Ecological State Category	D
Mean Ecological Importance Class	Low
Mean Ecological Sensitivity Class	Moderate
Ecological Category (SASS only)	C
Endemic species	None
IUCN Red List species	None
Macroinvertebrate Thermal Sensitivity Index	
Thermal Sensitivity Score	20
Number of Taxa	13
Average Thermal Sensitivity Score per Taxon	1.54
Are there species with specific thermal requirements?	No



Are there species with specific oxygen requirements?	No

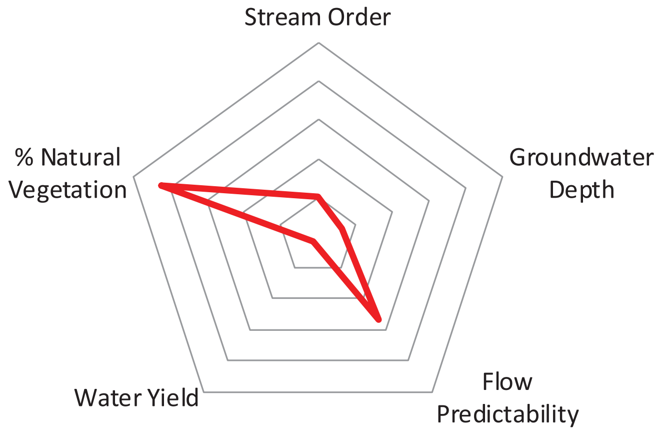
Quantifying thermal stress and assessing risk

Component	**Risk Rating**
Resilience	1
Severity - flow regime	5
Severity - physico-chemistry	4
Severity - habitat	2
Severity - biota	3
Overall Severity	**3.5**
Consequence	**2.9**
Likelihood	**5**
Significance	**14.4**
Risk	**High Risk**

BOX 3: Screening Process - Example 2

A farmer applies for a licence to abstract surface water from a river in the upper reaches of a catchment.

System Resilience: Total Resilience Score = 1.76

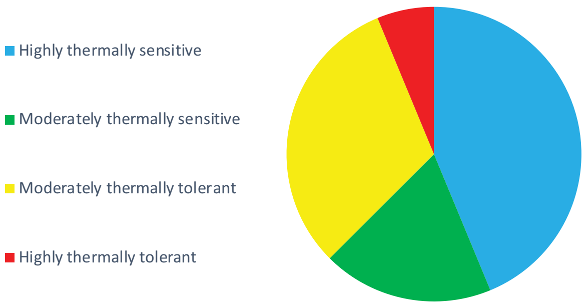


Hydrological, physico-chemical and habitat considerations:

Hydrology	
Naturalized streamflow per Water Management Area	1165 million m^3/a
Present Day streamflow per Water Management Area	990 million m^3/a
Present Day Mean Annual Runoff (MAR) as a percentage of Natural MAR	85%
Physico-chemistry (water quality)	
Dissolved oxygen concentration	> 8.0 mg/ℓ
Turbidity	Clear
Average inorganic nitrogen concentration	< 005 mg/ℓ (Oligotrophic)
Average inorganic phosphorus concentration	< 0.001 mg/ℓ (Oligotrophic)
Un-ionised ammonia (NH_3) concentration	0.007 mg/ℓ
Other chemicals present	Unknown
Potential for algal blooms	No
Potential for growth of invasive aquatic macrophytes	No
Habitat (geomorphology and riparian)	
Condition of instream habitat	Moderate
Condition of riparian habitat	High
Effect on sediment processes	Moderate

Sensitivity of river organisms:

Protected area	No
Critical biodiversity areas	Yes
Ecological support areas	No
NFEPA fish sanctuaries	Yes
National Freshwater Ecosystem Priority Area	Yes
Present Ecological State Category	A
Mean Ecological Importance Class	Very high
Mean Ecological Sensitivity Class	Very high
Ecological Category (SASS only)	A
Endemic species	*Pseudobarbus phlegethon* – ME level 1 *Lestagella penicillata* – RE level 1
IUCN Red List species	*Pseudobarbus phlegethon* - Endangered
Macroinvertebrate Thermal Sensitivity Index	
Thermal Sensitivity Score	48
Number of Taxa	16
Average Thermal Sensitivity Score per Taxon	3.0
Are there species with specific thermal requirements?	Yes



Are there species with specific oxygen requirements?	Yes

Quantifying thermal stress and assessing risk

Component	**Risk Rating**
Resilience	5
Severity - flow regime	1
Severity - physico-chemistry	1
Severity - habitat	4
Severity - biota	5
Overall Severity	**2.8**
Consequence	3.7
Likelihood	5
Significance	18.4
Risk	**Very High Risk**

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 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 (Poff et al. 2010), 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. Two workflow diagrams have been generated to guide the practitioner during the evaluation process (Figures 7 and 8).

The tools will be integrated into the FBIS and will generate a **Thermal Report Card** (see example in **Appendix 5**) 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, DWS 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.

Collecting 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.

The monitoring of water temperature on a sub-daily basis in South African rivers is currently limited and uncoordinated. Water resource practitioners, however, recognise the need for and value of such data. Here, we provide recommendations for collecting water temperature data, including logging frequency and technical information.

Electronic data loggers enable cheap and continuous collection of water temperature data. While such loggers may be programmed to log at a range of time scales, it is recommended that for the purposes of routine water temperature monitoring, hourly logging intervals are most appropriate. This is because a 24-hour period provides daily data on minimum, maximum, and average temperatures, as well as daily range. These parameters are most suited for freshwater ecological studies. In terms of minimum specifications for data loggers, the following criteria are important:

- Logging range: at least -10° - +50°C
- Resolution: 0.02°C
- Accuracy: 0.2°C
- Stability (drift): ≤ 1 minute per month and 0.1°C per annum

Depending on the project budget, available loggers include user-downloaded hardware, which is best achieved using a shuttle device, or a logger that transmits data to a base station connected to a mobile phone network. Practical guidelines on using and installing temperature data loggers are provided in **Appendix 6.**

Establishing Reference Indicators of Thermal Alteration and a Reference Thermograph

First, the practitioner needs to generate Reference Indicators of Thermal Alteration metrics (thermal metrics) and a Reference Thermograph for the site (Figure 7). The process for doing this varies depending on whether or not reference water temperature data or a reference thermograph exists for the site, or if the reference thermograph and reference thermal metrics need to be generated using modelled water temperature data. To date, very little water temperature data are available for reference sites. Reference thermographs have been developed for some rivers, where data exist. The process for generating Reference thermal metrics and reference thermographs, where data exist, will be automated within FBIS.

When the practitioner needs to use air temperature data to model water temperature, it will be acquired within FBIS. The choice of model will be automated to a default value based on hydrological region and geomorphological zone, which the user will be able to override if they have a site-specific air-water temperature model. A spatial framework has been developed to facilitate this process.

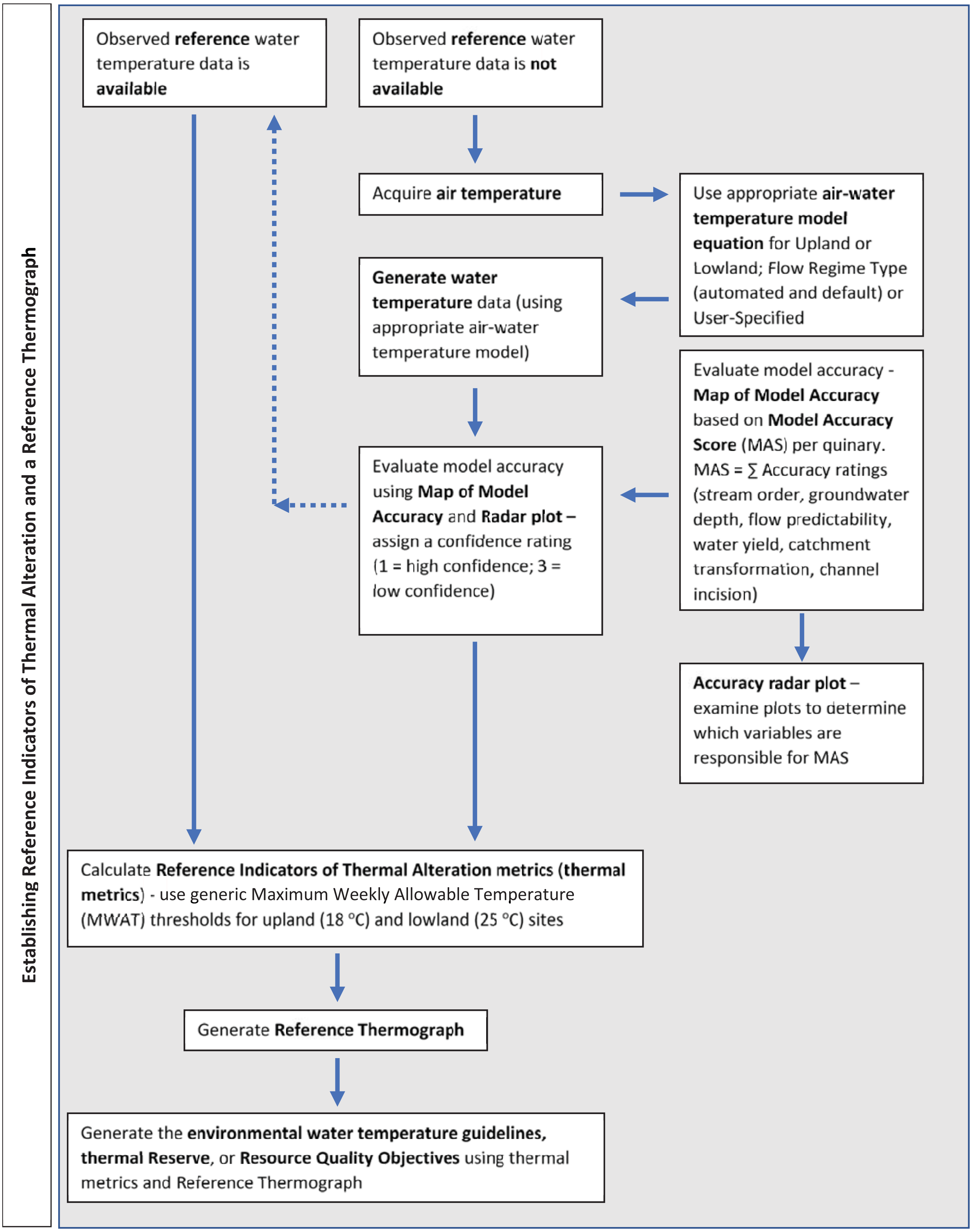


Figure 7. Work flow diagram for the Evaluation Process - establishing Reference Indicators of Thermal Alteration and a Reference Thermograph

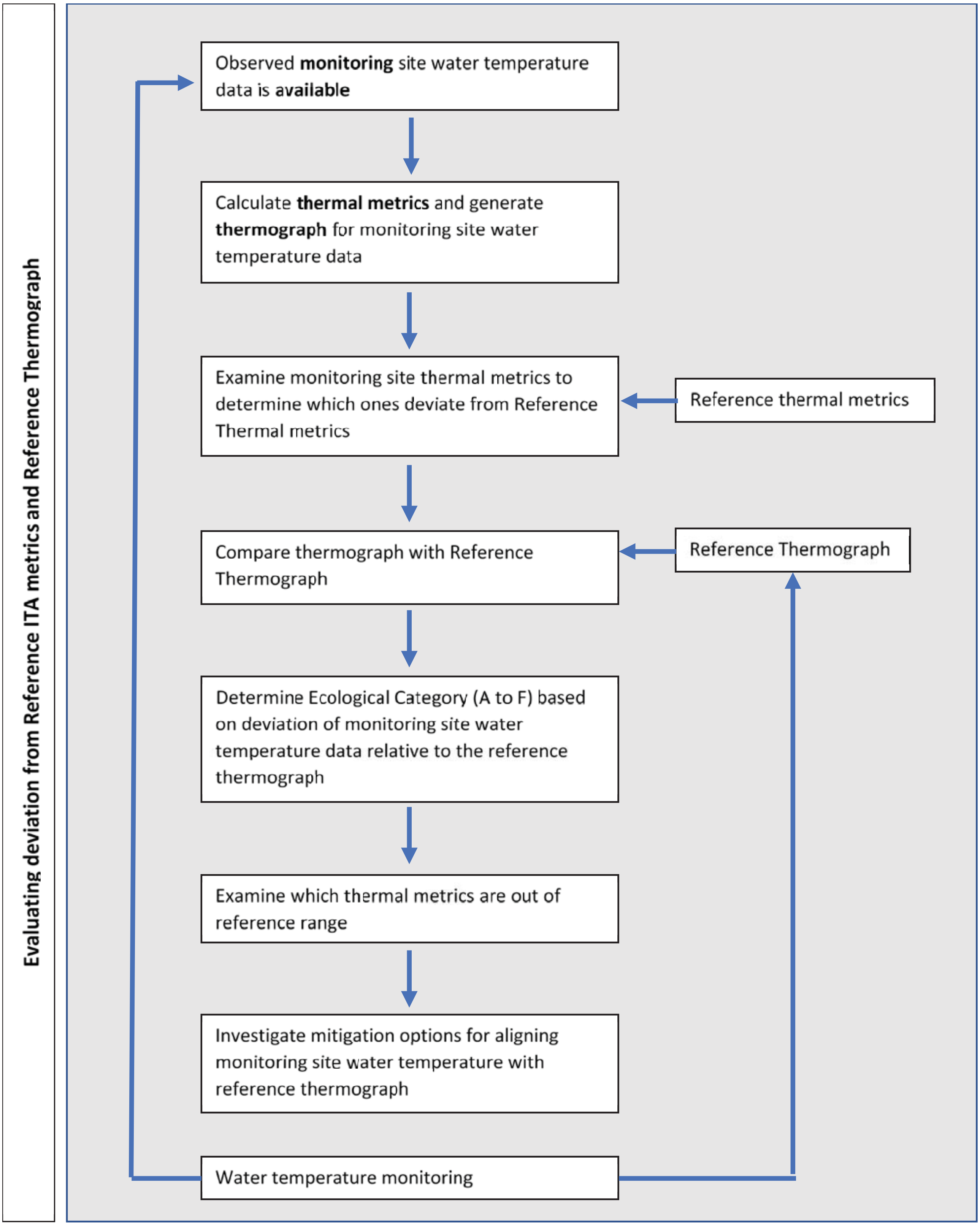


Figure 8. Work flow diagram for the Evaluation Process - evaluating deviation of water temperature monitoring data from Reference thermal metrics and Reference Thermograph, including the determination of the Ecological Category (A to F)

Spatial framework

A spatial framework which classifies each quinary catchment into "Upland" or "Lowland" geomorphological zones has been developed for South Africa (Figure 9). This serves as the framework within which air-water temperature models are applied and within which reference thermographs could be generated. The spatial database also contains additional information relevant to water temperature reserve assessments, including groundwater depth and estimated maximum daily range of water temperature. Maximum daily range of water temperature has been extrapolated to each quinary catchment using a relationship between stream order and maximum daily range (Rivers-Moore et al. 2008). The scores for the metrics used to provide guidance on potential system resilience and model accuracy is included in this database (see Tables 5 and 6).

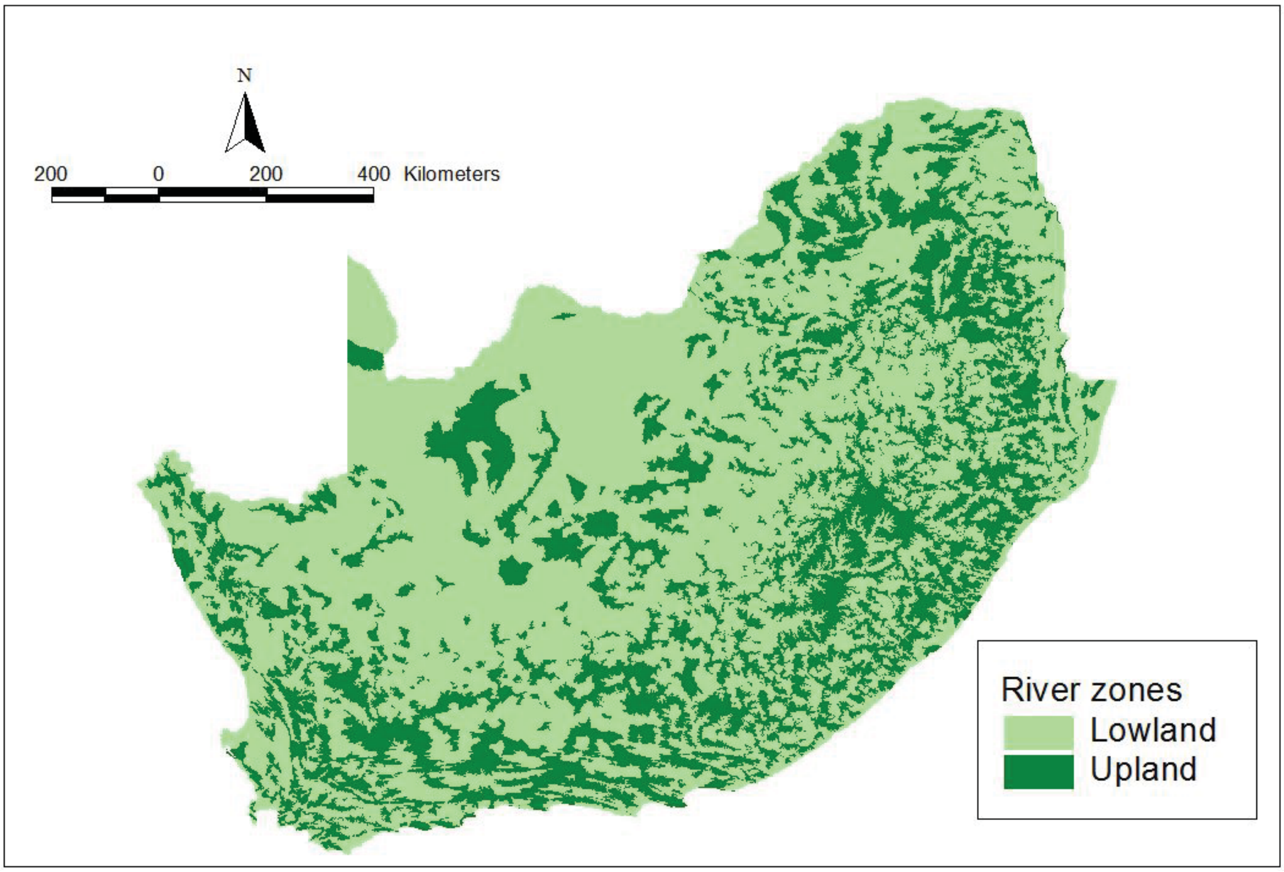


Figure 9. Quinary catchments classified as "Upland" or "Lowland" based on their geomorphological zones

Assessing model accuracy

Given the paucity of water temperature data in South African rivers, it is often necessary to model water temperature from air temperature. These models vary in complexity from simple regression models to stochastic and deterministic models (Dallas 2008). Several regression models have been developed for different parts of South Africa (see **Appendix 7**) and these are used to predict water temperatures from air temperatures. These models are likely to vary regionally and seasonally in terms of their accuracy due to regional differences in buffer and insulator variables such as groundwater inputs, site shading and channel incision, all of which confound the direct correlation between air and water temperature.

A database of variables able to assist with evaluating model accuracy has been developed for all quinary catchments (Table 6). 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 (Figure 10). This map allows users to evaluate model accuracy for a site based on five catchment variables. The user is then able to further explore which variables are responsible for this accuracy rating by examining radar plots, where those variables responsible for model accuracy are unpacked (Figure 11). In Figure 11, the site represented by the blue line has high model accuracy, while the site represented by the red line has low model accuracy. Within the spatial framework described, the relative importance of these variables in lowering model accuracy may be assessed.

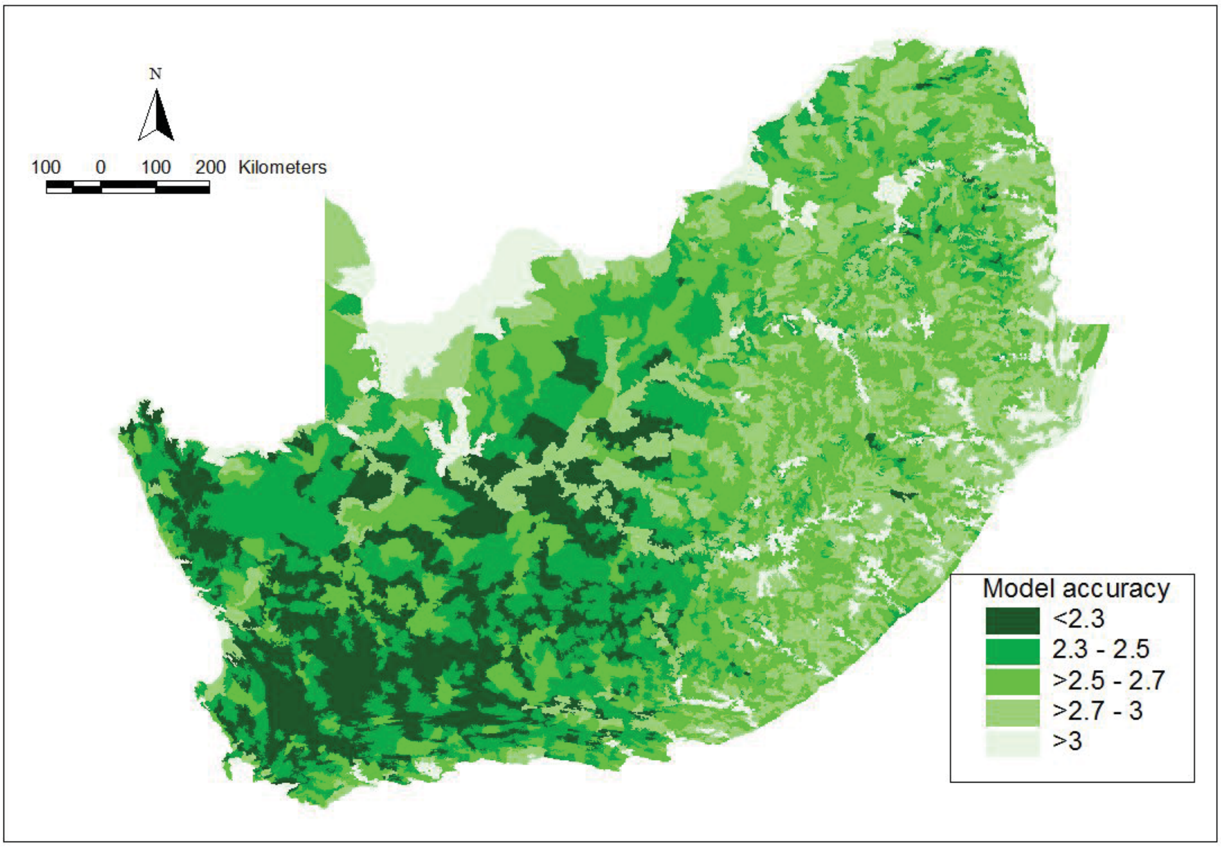


Figure 10. Map of Model Accuracy based on calculation of Model Accuracy Score for each quinary catchment (low accuracy = dark; high accuracy = light)

Table 6. Variables associated with quinary catchments for generating automated radar plots to assist in inferring model accuracy. Details of the source of the data and the method used are provided.

Variable	Source Data	Method	Model Accuracy (1 = greatest resilience; 0 = least resilience)
Stream order	DWS 1:500 000 rivers coverage	Each quinary catchment was assigned a stream order through a process of iteratively selecting all catchments intersected with stream order lines, beginning with stream order 1 and ending with stream order 7.	Larger rivers (higher stream orders) are more likely to have reached thermal equilibrium with air temperature than smaller streams (and will be less "flashy").
Groundwater depth	Colvin et al. (2007)	The mean groundwater depth was calculated for each quinary catchment using raster images Colvin et al. (2007).	Sites with little groundwater influence are likely to have better correlations with air temperature i.e. less buffering.
Flow predictability	Rivers-Moore et al. (2016)	Generated using simulated natural flow time series (Schulze et al. 2011) using the Indicators of Hydrological Alteration software (Richter et al. 1996).	Highly predictable flow regimes are more likely to have stable water temperature regimes.
Water yield	Schulze et al. (1997)	Calculated from national grids of monthly median precipitation and monthly A-pan evaporation. Water yield is based on monthly precipitation minus evaporation, as per the method of Rivers-Moore et al. (2007). Values are rescaled to values from 0-1 based on the monthly minimum value.	Catchments with low rainfall and high evaporation will have high thermal stress and are likely to be more variable and therefore poorer correlations with air temperature.
Channel incision	Schulze et al. (1997)	Relief ratio is the difference in elevation divided by the slope length within a catchment. These were calculated from the 1800x1800m digital elevation model using the quaternary catchments as the template. Values were rescaled 0-1, based on the maximum relief ratio, and then subtracted from 1, since best model accuracy is assumed to be achieved for flatter areas (low relief ratio scores).	Higher values for relief ratios indicate more tectonic influence and are a proxy for incision. Highly incised channels have shading and therefore poorer correlations with air temperature.

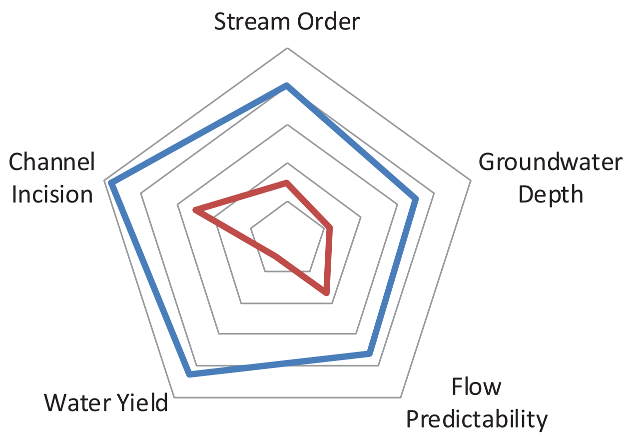


Figure 11. Radar plot showing the relative importance of five site variables potentially affecting model accuracy. The blue line represents a site with high model accuracy, while the red line represents a site with low model accuracy.

Calculation of Indicators of Thermal Alteration

The Indicators of Thermal Alteration (thermal metrics) describe an annual thermal regime using broad descriptive statistics such as mean annual temperature, annual coefficient of variability, predictability and maximum daily range. Thermal metrics also describe water temperature events in terms of their magnitude, frequency, duration and timing of extreme events. Details of thermal metrics generated using the Indicators of Thermal Alteration approach of Rivers-Moore et al. (2013a) are provided in **Appendix 8**. Ideally, reference thermal metrics and associated reference thermographs should be generated using either observed water temperature data, or simulated data based on air/water temperature models (in the absence of water temperature data).

Generation of Reference thermographs

Included in the Indicators of Thermal Alteration metric calculations is the determination of smoothed daily temperature means based on a seven-day moving average, and smoothed daily range using daily minima and maxima. These plotted time series are set within a 95% confidence envelope. To understand when and how thermal changes occur, metrics and envelopes of thermal variability should be used in combination, as a "weight of evidence" approach. Using a Sustainability Boundary Approach (SBA), which recognises the importance of thermal signature patterns, our approach defines smoothed daily mean water temperature and daily ranges that can immediately be observed to be within or outside a management envelope. Implicit in this approach is baseline variability, and the SBA is also robust regarding climate change, because the SBA boundaries (and allowable percentage departures) continue to apply.

The reference mean daily water temperature time series were generated for selected catchments using air/water temperature models (**Appendix 7**). Deviation from reference is described for Ecological Category (A to F) as follows: A/B: within 95% band; C/D: + 1 standard deviation; E/F: + 2 standard deviations (Figure 12). Difference between A and B categories; C and D categories, and E and F categories relate to frequency and duration. For example, for a C category, exceedance was once and for a short duration, while for D, exceedance was multiple times and for a longer duration.

Evaluating deviation of water temperature monitoring data from Reference

Calculation of Indicators of Thermal Alteration

When a water resource practitioner has hourly water temperature data from an impacted or monitoring site it is necessary to compare thermal metrics from the impacted site with the reference thermal metrics and monitoring site thermograph with the Reference Thermograph (Figure 8). This requires the conversion of sub-daily data from the impacted or monitoring site into daily data (mean, minimum and maximum daily water temperature). This process will be automated in FBIS to facilitate the relatively simple comparison of metrics from an impacted site with the appropriate Reference thermal metrics and Reference Thermograph. Determining the site-specific effect of a thermal stressor on a river, and evaluating whether the thermal ecological Reserve is met or not, requires at least one year's worth of sub-daily (one or two hourly) water temperature data for the site being assessed, and a comparable reference site from the same thermal type (see Rivers-Moore et al. 2013a for approach). An example of the outputs of this is provided in Table 7.

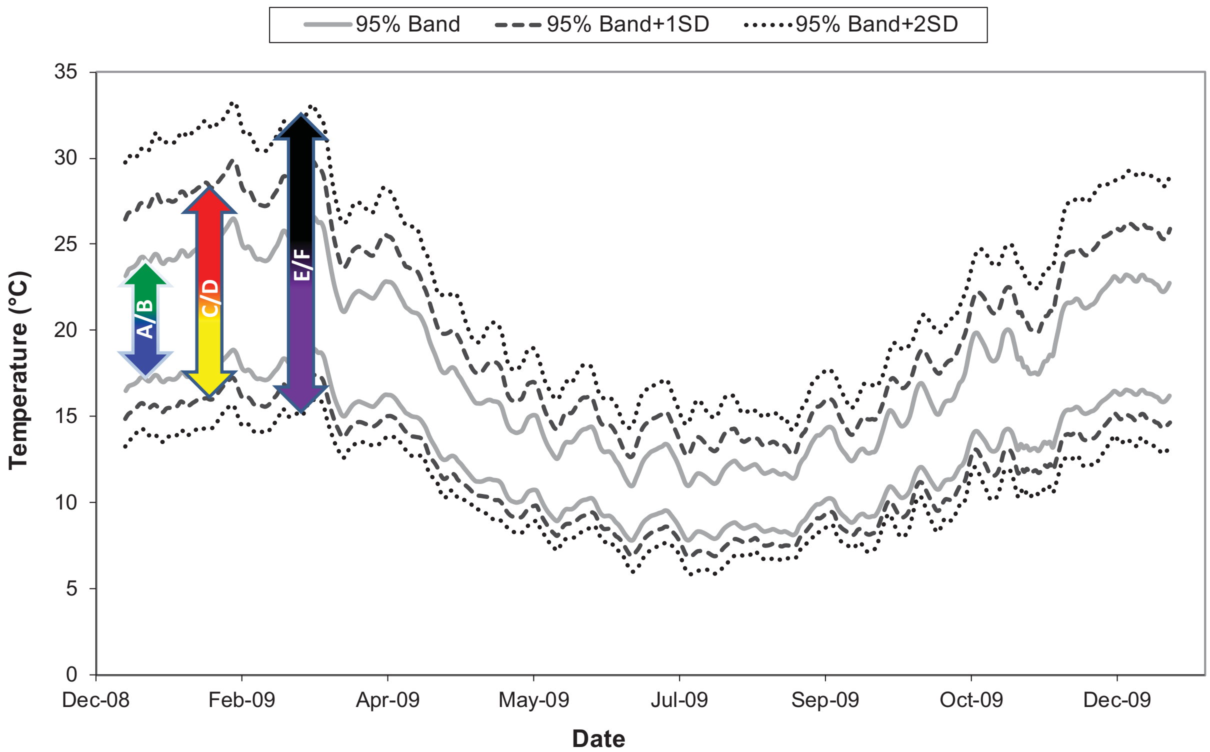


Figure 12. Reference thermograph indicating a reference condition thermal envelope plus one and two standard deviation. The associated Ecological Category for each is indicated.

Table 7. 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) (revised from Rivers-Moore et al. 2013a).

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*

Generation of monitoring site thermographs

The same automated process is undertaken to generate monitoring site thermographs as is for generating Reference thermographs. Smoothed daily temperature means based on a seven-day moving average, and smoothed daily range using daily minima and maxima are plotted to generate the thermograph.

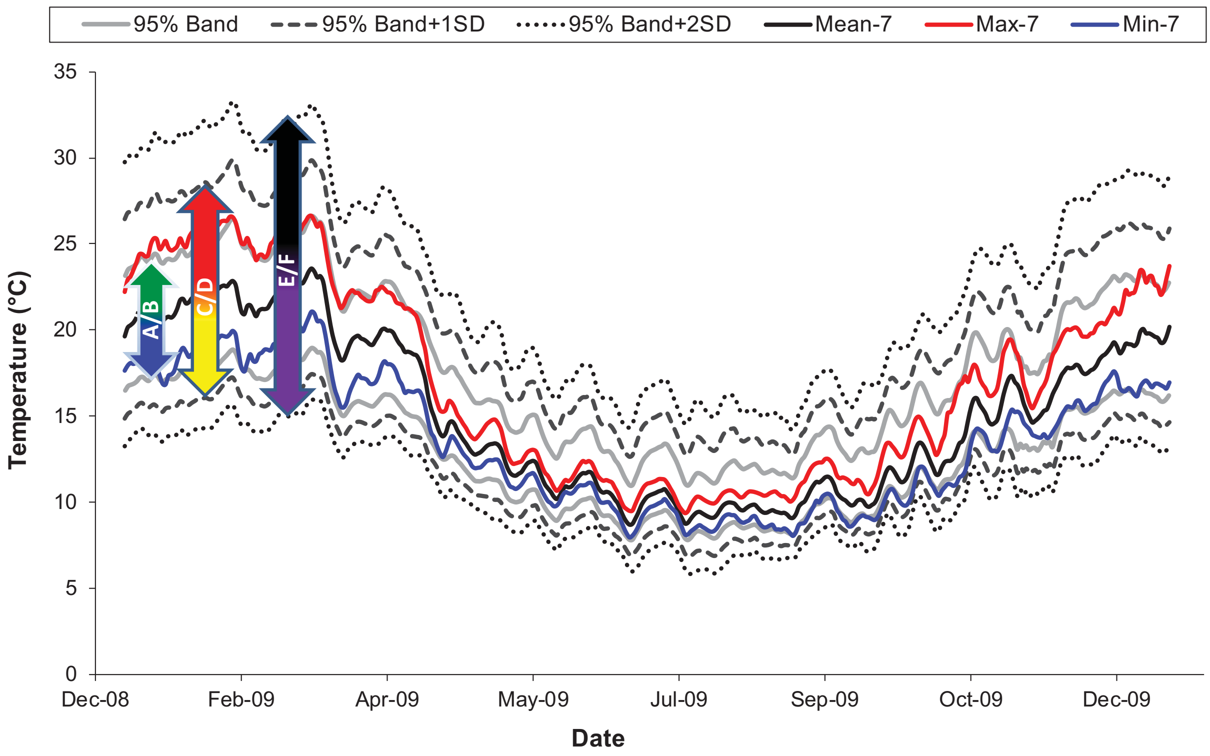
Determination of Ecological Category

Deviation from reference is linked to ecological categories to allow practitioners to determine the ecological condition of a site in terms of its thermal profile. Deviation from reference is described for Ecological Category (A to F) as follows: A/B: within 95% band; C/D: + 1 standard deviation; E/F: + 2 standard deviations (Figure 12). This comparison is only possible if sub-daily (preferably hourly) water temperature data have been collected.

As an example, time series for two rivers where water temperature should be similar, are plotted within a thermal reference envelope (Figure 13). In the case of the impacted site, the thermal condition may be classified as A/B during the winter months but deteriorates to an F during the summer months because the water temperature is too cold and fall well outside the reference bands for an F category.

In summary then, assessing whether the thermal Reserve has been met or not is based on a two-step process of checking whether the thermograph from the site being assessed falls within the thermal confidence envelope, and whether the suite of thermal metrics falls within a 10% range of the values of metrics from the reference site. If both steps fall within the recommended bounds, the site can be said to fall within acceptable thermal limits for the year of assessment and based on the reference site data. The thermal

Reserve is not met if one/both steps indicate that values fall outside the expected thermal range from the reference site.



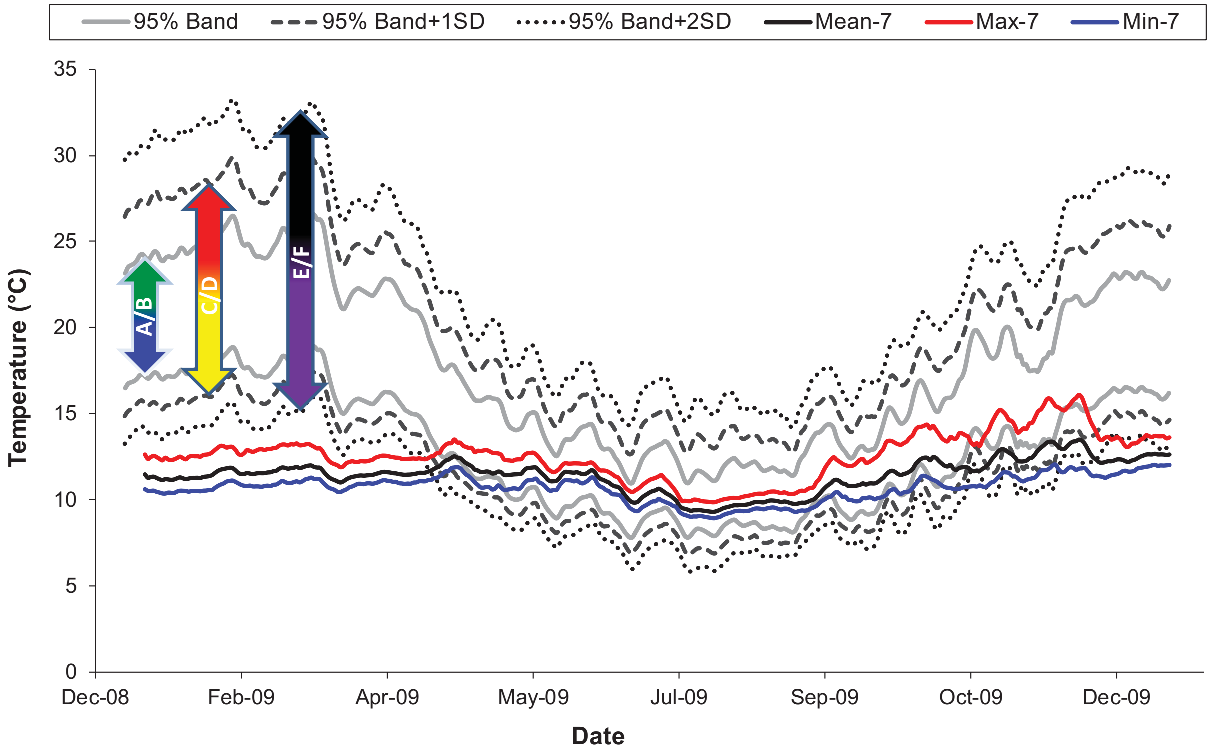


Figure 13. Assessment of daily temperature for two similar tributary sites using a reference thermograph. The frame on the top is for the Witte River, with largely natural water temperature, while the frame on the bottom shows water temperature downstream of an impoundment (Holsloot River).

Conclusions and the way forward

This manual serves to translate the results of many years of environmental water temperature research into practical management guidelines. We have integrated the best available information into a national spatial framework to provide both a decision-making process as well as reasonable contextual information on what to expect at thermally impacted sites at a quinary catchment scale. These data, however, largely serve as starting hypotheses that require testing using observed data informing either point-source impacts or trend analyses. The framework will become more accurate as more information on water temperature is added to the database, informing the reference thermal envelope curves and thermographs.

The next step 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. This 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 roll-out of a national water temperature monitoring programme, which has been strongly endorsed by all end-users and stakeholders involved in this project, needs to be prioritised. 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 Sustainable Development Goals (SDG), 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.

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Appendix 1. Key thermal impacts and their prevalence in South African rivers, outlining management and mitigation options

Thermal impact	Key points related to impact	Prevalence in South Africa	Management and mitigation options
Heated water from power plants	Power plants have different water withdrawal and consumption rates, depending on the cooling technologies in use. Once-through cooling uses a substantial supply of water, 99% of which is returned to the source. This water may be heated by as much as 14 °C. Discharge of heated water may impact receiving water bodies. The effect of heated effluents on receiving water bodies is variable, dependent on season and on the degree to which the heated effluent mixes with the receiving water. The critical aspect of heated discharges was related to the pattern of discharge. The most deleterious effect occurred when a surface layer of heated water covered the whole river, as this "concentrated" the temperature increase and prevented organisms that periodically surface from doing so comfortably. Other potential patterns included a narrow band of hot water on top of a cold layer (a common pattern in fast-flowing narrow streams) and the complete horizontal mixing of the discharge water with the river water, which would normally result in an overall temperature increase of only a few degrees and hence with a lesser impact.	There are 13 power plants in Mpumalanga and two in Limpopo. All plants use either wet-recirculating closed-loop cooling technologies or dry cooling approaches. Water from these plants is not released into rivers.	For cases where heated water from a power plant is released into the receiving water body, the options for reducing the temperature of the discharged water need to be explored, such as use of multiport thermal diffusers. Thermal diffusers release the discharge from multiple round nozzles as high-velocity jets that entrain ambient water and dilute and cool the hot water. This ensures that the discharged water matches a downstream temperature target of the receiving water body.
Heated industrial effluent	Industries that discharge heated effluent include oil refineries, the pulp and paper industry, the sugar industry and the textile industry. The effect of heated effluents on receiving water bodies is variable, dependent on season and on the degree to which the heated effluent mixes with the receiving water. As heated industrial discharges are frequently linked to other forms of pollution (e.g. chemical pollution), toxicity of chemicals may be significantly increased when released in association with elevated temperature.	Water from heated industrial effluents is seldom released into rivers.	For cases where heated industrial effluent is released into the receiving water body, the options for reducing the temperature of the discharged water need to be explored, as per heated water from power plants.

Thermal impact	Key points related to impact	Prevalence in South Africa	Management and mitigation options
Mining and mine dewatering	Dewatering and groundwater control is an important part of many open pit and underground mines, especially when mining is below the water table groundwater. A key aspect of mine dewatering systems is that they will generate water from pumped wells or sumps, from flowing drains, and from surface water collection systems. This water may require treatment before it is discharged into the receiving water body.	Discharge of water from mining or mine dewatering may be heated. The Water Research Commission recently published an online South African Mine Water Atlas, including groundwater vulnerability maps, available at: http://www.wrc.org.za/programmes/mine-water-atlas/	Release of water from mines is normally treated before release into receiving water bodies. This treatment should include reduction in temperature if the discharge is heated.
Heated water from wastewater treatment works (WWTWs) and water treatment works (WTWs)	Water discharged from municipal WWTWs may be heated, depending on the water received for treatment. The likely impact of the heated effluent on the receiving water body is often not the most significant impact but may exacerbate existing water quality conditions.	Centralized WWTWs and WTWs are one of the most common systems for the treatment of domestic wastewater in South Africa. Approximately 56% of the 1 150 WWTWs and 44% of the 962 WTWs are in a poor or critical condition and in need of urgent rehabilitation. Although WWTWs can be effective at reduction of biochemical oxygen demand (BOD) and pathogen load, it is impossible for the characteristics of the effluent to match the characteristics of the water in the receiving system. Water temperature is not explicitly included in wastewater treatment.	There are many methods for reducing thermal load. Approaches include 1) reducing the temperature of wastewater before it reaches the WWTW, 2) modifications that can be made inside the WWTW, 3) changes in the way effluent is discharged from the WWTW, and 4) direct cooling of the effluent after treatment and prior to discharge. Generally, each WWTW has a unique set of parameters and conditions that need to be considered when reducing its thermal load.
Flow modification (river regulation and impoundments)	Flow regulation exerts a moderating influence on the downstream thermal regime, including diurnal and seasonal thermal constancy. An alteration in the volume of discharge affects the thermal capacity of a river; and decreasing flow is likely to increase daily water temperature, including daily	Of the approximately 5 000 registered dams, the vast number (3 832) are small dams (less than 12m) serving farms and municipalities. In addition, the small dam dataset contains more	Mitigation measures to reduce the undesirable effects of an impoundment include modification of its structure or operation, or through changes

Thermal impact	Key points related to impact	Prevalence in South Africa	Management and mitigation options
	maxima. Effects may include an increase in mean water temperature and a reduction in the extent of variability between temperature extremes, as well as delayed seasonal temperature maximum. The extent to which an upstream impoundment modifies downstream thermal conditions depends on operational variables (release depth, discharge pattern), limnological variables (retention times, stratification pattern and thermal gradients) and the position of the impoundment along the longitudinal profile of the river. Epilimnetic (top) releases may increase water temperature, while hypolimnetic (bottom) releases may decrease temperature. Seasonality may be suppressed below an impoundment, particularly in the summer months. Impoundments affect downstream thermal regimes for some distance and reset distance below an impoundment may be up to 86 km downstream. These disrupt multiple components of a thermograph (timing, duration, frequency and magnitude of thermal events), all of which result in asynchronous biological cues for life history stages such as spawning, migration, egg development and transition to different life history stages (e.g. pupation).	than 165 000 dams of which just over 600 are large dams. Downstream flow impacts from an impoundment includes disruption of the natural process of water temperature reaching equilibrium temperature with the atmosphere. Ecologically, this is expressed as a disruption in natural turnover rates of aquatic communities. The downstream distance required before a river returns to reference state is defined as its “reset distance” and is related to flow volumes.	to the management of the catchment within which the impoundment is situated. They include changes to inlet structure configuration, artificial mixing by a mechanical mixer or compressed air, flushing to reduce residence times, and multi-level outlet works. The latter can allow dam operators to blend warm water from the top of the dam with cooler water at other levels, or to simply select a depth from which to withdraw water, in an attempt to match a downstream temperature target of the receiving water body.
Surface water abstraction	Withdrawal of excessive quantities of water from a river can significantly impact its capacity to absorb heat. The smaller volume of water remaining instream will heat (and cool) more quickly and dissipate heat from a warm discharge less effectively. Surface water abstraction leads to decreased flow depth and velocity, which have non-linear impacts on summer maxima and diurnal range.	Abstraction of surface water is perhaps one of the most common practices and thus likely to have one of the greatest impacts on thermal conditions of rivers in SA.	Factors to consider in managing and mitigating thermal impacts on rivers caused by water abstraction include timing of surface water abstraction such that abstraction is restricted to medium and high flow periods, when the impact of water abstraction on water temperature will be less

Thermal impact	Key points related to impact	Prevalence in South Africa	Management and mitigation options
			significant, especially in the Western Cape, where hot summers coincide with lowest flows. Ensuring that tributaries remain intact also provides a critical input of water to mainstem rivers where water abstraction is occurring. Where present, tributaries can also be important in mediating stream temperature in mid-sized channels (stream order 3–4).
Inter-basin water transfer (IBT) and flow augmentation	Inter-basin transfer schemes constitute "the transfer of water from one geographically distinct river catchment to another; or from one river reach to another. IBT's impact water temperature in both the donor system and the receiver system. Depending on the timing and volumes abstracted, donor systems are likely to experience greater thermal maxima and daily range, because of reduced flow volumes. Conversely, thermal impacts on receiver systems are likely to include increased thermograph homogeneity and reduced thermal seasonality due to the buffering effects from increased flow. Augmentation of flow through IBT transfers may result in change of volume and temperature of the recipient river. Thermally, there is mixing of different volumes of water at different thermal equilibriums, although this likely depends on the length of canals between donor and recipient system.	Approximately 3 000 million m3/a of the surface yield is moved via about 30 inter-basin transfers from water-rich donor catchments to water-poor areas in the country where in-basin requirements exceed available supplies. Many of these IBTs have operated for more than 20 years.	The technical and economic aspects of Inter-basin transfers often overshadow and supersede their environmental consequences. From a thermal perspective, IBTS between donor and recipient systems that have similar thermal characteristics, will have less of a thermal impact.
Groundwater abstraction	Thermal interaction of streams and rivers with groundwater occurs both through upwelling of deeper catchment groundwater and bidirectional (hyporheic) exchange between	The realistically accessible groundwater potential in South Africa is about 4 500 million m3/a of the	Groundwater flow in an aquifer is governed by the aquifer's intrinsic

Thermal impact	Key points related to impact	Prevalence in South Africa	Management and mitigation options
	shallower groundwater and surface along relatively short groundwater flow paths (centimeters to tens of meters). Instream/groundwater exchange processes in channels buffer against the influence of air temperature and heating by solar radiation. Groundwater dominated rivers buffer seasonal and extreme events and are generally cooler and more stable than rivers whose flow is derived primarily from surface flow. A natural groundwater river is likely to be less vulnerable to climate change.	estimated sustainable potential groundwater yield of around 7 500 million m3/a, widely distributed across the country. While groundwater is currently an under-utilized resource on a national level, it is totally over-utilized in many areas and groundwater levels are over abstracted.	characteristics (shape, size, permeability etc) but also by its recharge, largely produced by infiltration of precipitation. Knowledge of groundwater pollution is limited because monitoring information is only available at a national or regional level, while pollution impacts are generally localised and groundwater compliance monitoring is not yet sufficiently operational. From a thermal perspective, abstraction of groundwater may affect surface water temperature in river systems that are groundwater dependent.
Land-use change – urban runoff/catchment hardening (impermeable surfaces)	When land is urbanized changes in the land surface composition occurs, with concomitant changes in runoff, especially water temperature. Impermeable surfaces, such as roads and buildings, absorb and store solar radiation resulting in surface temperature that exceed air temperature. There is a relationship between increased urbanization and increased surface water runoff temperature.	Thermal impacts from urbanization is an issue associated with all urban and semi-urban areas in South Africa. The risk to receiving water bodies of thermal impacts from runoff from urbanized areas is however dependent on the sensitivity of the receiving water body, as well as the other impacts within the area.	Preventative methods involve applying techniques which are designed to reduce stormwater runoff and mimic natural water balance. This may involve using infiltration methods which can reduce the volume and temperature of the water conveyed to a storm sewer network. Preventative measures are the preferred stormwater management options as they not only

Thermal impact	Key points related to impact	Prevalence in South Africa	Management and mitigation options
			reduce thermal loading to receiving streams, they also improve water quality, maintain water balance and reduce erosion. Bioretention is a Best Management Practice that is proven to reduce runoff and improve water quality, including thermal pollution.
Agricultural/irrigation return flows	Irrigation return flows are the part of artificially applied water that is not consumed by evapotranspiration and that either drains to the water table or runs off to a surface-water body. Water temperature in the return flows may increase or decrease as it flows in irrigation canals, ditches and furrow-irrigated fields depending on the season and shading.	Agriculture currently uses 61% of South Africa's freshwater. It is estimated that 10% of the gross irrigation demand is the typical irrigation return flow volume. Climate change may also increase the agricultural demand for water due to higher temperature, and a reduced ability to rely on rain-fed agriculture.	Water in wide, shallow irrigation canals will be more likely to have an elevated water temperature. Mitigation options include shading irrigation canals, ditches and furrows; and modifying seasonal timing of releases, although this is likely to conflict with agricultural needs.
Modification of riparian vegetation	Riparian vegetation affects water temperature by adsorbing some of the incoming radiation, emitting longwave radiation and creating a microclimate, which in turn affects evaporation, conduction, ground and water temperature. Removal of riparian vegetation exposes water to increased direct solar radiation, which leads to higher temperature, particularly during summer low flows, and greater temperature ranges and fluctuations. Loss of riparian shading can be caused by a wide range of human activities, including urbanization, timber harvest, road cuts, forest fires, land clearing for agricultural purposes, and livestock grazing. Removing riparian forests can	Removal of riparian vegetation in South Africa has not been quantified although it is considered widespread. Encroachment of alien vegetation is a significant problem in many river systems. The extent and type of alien vegetation may influence water temperature in streams and rivers.	Maintaining indigenous riparian vegetation along rivers assists with the maintenance of a natural thermal profile, typically resulting in lower water temperature.

Thermal impact	Key points related to impact	Prevalence in South Africa	Management and mitigation options
	increase summertime stream temperature, because decreased shade following harvesting or road building results in up to 10-fold increases in solar radiation reaching the water surface. Smaller streams with canopy-like vegetation that shade the stream are more likely to experience significant temperature changes, notably warming with increases in peak or average stream temperature in summer, if the vegetation is removed. In comparison, reduction in riparian shading in larger rivers has less of an effect on water temperature and riparian vegetation has a significant influence on the temperature of order 1-2 streams and little effect on order 5+ streams.		
Modification of channel morphology	Channel morphology affects the temperature regime within a given channel because the effect of solar radiation on water temperature at the stream surface depends on stream width, depth and flow velocity. Physical modification of the river channel may affect water temperature by impacting hyporheic exchange and atmospheric heat exchange, thereby increasing channel width-to-depth ratio; and channel straightening and simplification typically reduces hyporheic exchange. For a given stream discharge, a shallower, wider channel heats up and cools down faster than its deeper, narrower equivalent; and typically channels that are widened and shallower are generally warmer with higher daily maxima.	Modification of river channels in South Africa has not been quantified, but is considered widespread, although often localised.	Maintaining an intact, natural river channel assists with the maintenance of a natural thermal profile, typically resulting in lower water temperature.
Global climate change	Primary climate change drivers are precipitation, air temperature and evaporative demand, and the combination of these is likely to lead to increased water temperature in some regions. Global climate change drivers directly affect the quantity of water in rivers by changing run-off patterns (e.g. mean values, flow variability, duration and timing), increasing the frequency and intensity of extreme events (droughts and floods), and changing groundwater recharge rates.	Predictions are not uniform within South Africa and climate change is likely to impact most strongly on the western regions, with less of an impact as one goes eastwards. Air temperature is predicted to increase throughout SA, with greatest increases in winter rainfall regions. Rainfall is	There is no direct way to mitigate the impacts associated with global climate change, which is recognised as an additional, amplifying driver of system variability and cannot therefore be viewed in isolation from other stressors.

Thermal impact	Key points related to impact	Prevalence in South Africa	Management and mitigation options
		predicted to increase in the east and decrease in the west.	

Appendix 2. Effects of changes in water temperature on physico-chemical parameters (water quality). Modified from DWAF (1996) and Dallas and Day (2004).

Parameter	Effect
Dissolved oxygen	Higher temperature reduces the solubility of dissolved oxygen in water, decreasing its concentration and thus its availability to aquatic organisms. If the organic loading is high, oxygen depletion is further accelerated by greater microbial activity at the higher temperature. High water temperature combined with low dissolved oxygen levels can compound stress effects on aquatic organisms. The depletion of dissolved oxygen in conjunction with the presence of toxic substances can also lead to a compounded stress response in aquatic organisms. Under such conditions increased toxicity of zinc, lead, copper, cyanide, sulphide and ammonia have been observed. The Target Water Quality Range for dissolved oxygen concentrations (in terms of percentage saturation) in aquatic ecosystems is 80 % to 120 % of saturation (DWAF 1996). Concentrations < 0.6 mg/ℓ are generally harmful to aquatic organisms, with the exception of those adapted to low dissolved oxygen concentrations. Dissolved oxygen concentrations and percent saturation are related, but not equivalent, and thus mg/ℓ is a more appropriate value (Dissolve oxygen concentration decreases as water temperature increase; i.e. 80% saturation at 10 ^{0}C is 9.02 mg/ℓ and at 25 ^{0}C is 6.59 mg/ℓ). The significance of dissolved oxygen depletion to aquatic organisms depends on the frequency, timing and duration of such depletion. The following table has been modified from DWAF (1996). It provides some guidance on duration, but as data do not exist, does not take frequency, timing and duration explicitly into account.

Insignificant/ non-harmful	Small/ potentially harmful	Significant/ slightly harmful	Great/ harmful	Disastrous/ extremely harmful
7-day Mean DO concentration > 8 mg/ℓ	7-day Mean DO concentration 7 to 8 mg/ℓ	7-day Mean DO concentration 6 to 7 mg/ℓ	7-day Mean DO concentration 4 to 6 mg/ℓ	7-day Mean DO concentration < 4 mg/ℓ

Parameter	Effect
Turbidity	An increase in the turbidity may lead to a decrease in water temperature as more heat is reflected from the surface and less absorbed by the water (DWAF 1996). A narrative describing turbidity is as follows, with increasing turbidity: clear, discoloured, opaque and silty.

Clear	Discoloured	Opaque	Silty

Parameter	Effect

Trophic status based on average inorganic nitrogen concentration

The processes of ammonification, nitrification, denitrification, and the active uptake of nitrate by algae and higher plants, are regulated by water temperature, oxygen availability and pH. Changes to water temperature and pH affect the rates at which these processes occur and the concentration of inorganic nitrogen present in water (DWAF 1996). The concentrations associated with different trophic states are as follows (from DWAF 1996):

< 0.5 mg/ℓ (Oligotrophic)	0.5 to 2.5 mg/ℓ (Mesotrophic)	2.5 to 10 mg/ℓ (Eutrophic)	> 10 mg/ℓ (Hypertrophic)

Trophic status based on average inorganic phosphorus concentration

Water temperature, light and the availability of other nutrients play an important role in limiting plant growth. High temperature favour the release of phosphorus from the sediments. The concentrations associated with different trophic states are as follows (from DWAF 1996):

< 0.005 mg/ℓ (Oligotrophic)	0.005 to 0.025 mg/ℓ (Mesotrophic)	0.025 to 0.25 mg/ℓ (Eutrophic)	> 0.25 mg/ℓ (Hypertrophic)

Un-ionised ammonia (NH_3) concentration

The toxicity of ammonia is directly related to the concentration of the un-ionized form (NH_3), the ammonium ion (NH_4^+) having little or no toxicity to aquatic biota. An increase in water temperature results in an increase in the relative proportion of un-ionized ammonia in solution, and hence an increase in toxicity to aquatic organisms. For every 10°C increase in temperature, the ratio of unionized ammonia to ammonium doubles. This is further exacerbated if pH also increases. Ammonia is a common pollutant and is one of the nutrients contributing to eutrophication. Commercial fertilizers contain highly soluble ammonia and ammonium salts. Other sources of ammonia include fish-farm effluent (un-ionized ammonia), sewage discharge, discharge from industries that use ammonia or ammonium salts in their cleaning operations, manufacture of explosives and use of explosives in mining and construction, atmospheric deposition of ammonia from the distillation and combustion of coal, and the biological degradation of manure. Ammonia criteria for aquatic ecosystems are calculated from the total ammonia concentration, that is, the sum of the NH and NH concentrations. The Target Water Quality Range, Chronic Effect Value and Acute Effect Value for un-ionised ammonia in aquatic ecosystems are as follows (from DWAF 1996):

< 0.007 mg/ℓ (Target Water Quality Range)	0.015 mg/ℓ (Chronic Effect Value) to 0.06 mg/ℓ	0.1 mg/ℓ (Acute Effect Value)

Chemical Toxicity

High water temperature can increase the solubility and thus toxicity of certain compounds, including heavy metals such as cadmium, zinc and lead, as well as compounds like atrazine, cyanide, fluoride, phenol, selenium and xylene.

Appendix 3. Biological effects resulting from thermal change in rivers have been split into five categories, namely physiological and metabolic, phenological, reproductive success and fitness, behavioural, and ecological responses. The response variables within each category have been described in relation to temperature (from Dallas and Ross-Gillespie (2015).

Major effects	Response variables	General findings summarised from studies of response variables in relation to temperature
Physiological and metabolic	Performance curves	Performance is optimal at intermediate temperatures and outside of this range it is reduced.
	Growth rates	Growth rates increase with increasing temperature to an optimum, after which they begin to decline and tend to zero as thermal tolerance limits are approached. Temperature for optimal growth do not translate to temperature for optimal growth efficiency, emergence success or length of emergence period.
	Size at emergence	Faster growth at warmer temperature results in smaller size at maturity. Colder temperature results in slower growth, longer development time and larger size at maturity.
	Secondary productivity and assimilation	Secondary productivity is increased at warmer temperature.
	Respiration	Respiration is increased at warmer temperature and oxygen may become a limiting factor at warmer temperatures.
Phenological	Total development time	Faster growth rates at warmer temperature leads to shorter development periods and may result in early emergence cues in aquatic insects.
	Voltinism flexibility	Warmer temperature with greater variability promotes more generations produced in a year (bi-, tri- or multi-voltinism) and more flexible life histories; while more conservative, less flexible life histories are selected for under colder, more stable, conditions. Cold temperature results in slower growth rates, longer development periods and delayed emergences in insects, and are normally associated with fewer generations over year (univoltine life cycles).
	Timing and duration of emergence	Extended, unsynchronised emergence periods in aquatic insects at warm temperatures, more synchronous and shorter emergence at cold temperatures.
	Timing of fish spawning	Fish spawning is often cued into water temperature and changes in water temperature may alter timing. Reduced water temperature resulting from hypolimnetic releases from an impoundment may

Major effects	Response variables	General findings summarised from studies of response variables in relation to temperature
		delay spawning (often in direct proportion to the proximity to the dam), while epilimnetic releases may result in early spawning.
Reproductive success and fitness	Fecundity	Fecundity is directly related to body size of females at maturity and so declines with higher temperature.
	Rates and success of egg development and hatching	Eggs develop faster with increasing temperature that are within egg development limits. Temperatures that result in faster egg development are not always those that result in highest hatching success. Hatching success is usually highest at temperatures slightly lower than those that promote fastest development. High temperatures approaching development limits lead to deformed or retarded development and lower hatch success.
	Juvenile survival and recruitment	Low temperatures below species-specific thresholds may induce egg diapause and similarly temperatures above species-specific thresholds may terminate diapause. Increased temperatures result in higher juvenile mortality rates.
Behavioural	Migration	Organisms migrate or move to a zone of thermal preference when introduced to a wide range of temperatures; even if this means foregoing access to resources such as food.
	Drift	Dramatic and sudden increases in temperature may lead to catastrophic drift in aquatic insects to escape. Gradually increased temperatures may lead to increased amplitude of diel drift.
Ecological	Species richness	Richness generally increases with increased annual water temperature variation. Increased variation in diurnal temperatures favours certain species while negatively affecting others.
	Species composition	Species composition is generally more diverse in habitats experiencing a wider range of annual and diurnal temperatures.
	Density	Latitudes and altitudes promoting optimum temperature ranges for a wider range of species result in greatest densities and abundances of those species.
	Distribution patterns	Water temperatures control aquatic species distribution patterns. Cool headwaters represent ancestral habitat of many aquatic insects. Colonisation of lower reaches and lentic waters involved adaptation to warmer thermal conditions. Cool waters represent thermal refugia for cold adapted stenotherms. Warm stenotherms and eurytherms are able to colonise habitats exhibiting a wide range of temperatures.

Appendix 4. Thermal risk assessment matrix – overview of spreadsheet for assessing risk

Component	Category	Generated	Descriptions/ questions	Rating 1	Rating 2	Rating 3	Rating 4	Rating 5
Severity	**System Resilience**	Automated	Total Resilience Score (TRS)	Very high resilience (> 3.5)	High resilience (> 3.2 to 3.5)	Medium resilience (> 3.0 to 3.2)	Low resilience (2.7 to 3.0)	Very low resilience (< 2.7)
Severity	**Hydrological regime - Score impact of activity on flow regime (quantity, pattern, timing, water level and assurance of instream flow). Based on maximum rating.**			**Insignificant/ non-harmful**	**Small/ potentially harmful**	**Significant/ slightly harmful**	**Great/ harmful**	**Disastrous/ extremely harmful**
		Automated	Present-Day Mean Annual Runoff (MAR) as a percentage of Natural MAR	> 80 % of MAR	70 to 80 % of MAR	60 to 70 % of MAR	40 to 60 % of MAR	< 40 % of MAR
Severity	**Physico-chemical (water quality) - Score impact of thermal activity on water quality based on physico-chemical sub-categories. Based on maximum rating.**			**Insignificant/non-harmful**	**Small/potentially harmful**	**Significant/slightly harmful**	**Great/harmful**	**Disastrous/extremely harmful**
		User enters data	What is the dissolved oxygen concentration?	Seven day mean dissolved oxygen concentration > 8 mg/l	Seven day mean dissolved oxygen concentration 7 to 8	Seven day mean dissolved oxygen concentration 6 to 7	Seven day mean dissolved oxygen concentration 4 to 6 mg/l	Seven day mean dissolved oxygen concentration < 4 mg/l
		User enters data	Turbidity: Is the river clear, discoloured, opaque or silty?	Clear	Clear	Discoloured	Opaque	Silty
		User enters data	What is the trophic status based on average inorganic nitrogen concentration?	< 0.05 (Oligotrophic)	< 0.5 mg/l (Oligotrophic)	0.5 to 2.5 mg/l (Mesotrophic)	2.5 to 10 mg/l (Eutrophic)	> 10 mg/l (Hypertrophic)
		User enters data	What is the trophic status based on average inorganic phosphorus concentration?	< 0.001 (Oligotrophic)	< 0.005 mg/l (Oligotrophic)	0.005 to 0.025 mg/l (Mesotrophic)	0.025 to 0.25 mg/l (Eutrophic)	> 0.25 mg/l (Hypertrophic)
		User enters data	What is the concentration of un-ionised ammonia (NH_3)?	< 0.007 mg/l (Target Water Quality Range)	0.007 to < 0.015 mg/l	0.015 mg/l (Chronic Effect Value) to 0.06 mg/l	0.06 to < 0.1 mg/l	0.1 mg/l (Acute Effect Value)

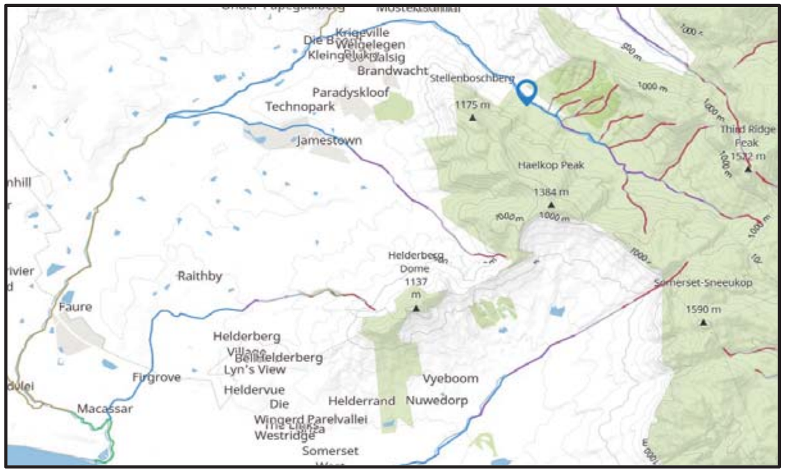
Component	Category	Generated	Descriptions/ questions	Rating				
				1	2	3	4	5
		User enters data	Are other chemicals present and in what concentrations atrazine, cadmium, cyanide, fluoride, lead, phenol, selenium, xylene and zinc)	None present	Present but in low concentrations	Present in moderate concentrations	Present in high concentrations	Present in extremely high concentrations
		User enters data	Assess the presence and extent of algae visible at the site	No algae present	Small amount of algae present, in isolated patches	Moderate amount of algae present; in several patches on surface water	Large amounts of algae present, large sections of surface water covered	Very large amounts of algae present; extensive covering of surface water
		User enters data	Assess the presence and extent of invasive aquatic macrophytes visible at the site	No macrophytes present	Small amount of macrophytes present, in isolated patches	Moderate amount of macrophytes present; in several patches on surface water	Large amounts of macrophytes present, large sections of surface water covered	Very large amounts of macrophytes present; extensive covering of surface water
Severity	**Habitat (Geomorphology + Vegetation) - Score impact of activity on the character and condition of the instream and riparian habitat and sediment processes. Based on maximum rating.**			**Insignificant/ non-harmful**	**Small/ potentially harmful**	**Significant/ slightly harmful**	**Great/ harmful**	**Disastrous/ extremely harmful**
		User enters rate	Will the activity affect the instream habitat?	Very low	Low	Moderate	High	Very high
		User enters rate	Will the activity affect the riparian habitat?	Very low	Low	Moderate	High	Very high
		User enters rate	Will the activity affect sediment processes?	Very low	Low	Moderate	High	Very high

Component	Category	Generated	Descriptions/ questions	Rating				
				1	2	3	4	5
Severity	**Biota - Sensitivity of aquatic biota and conservation importance based on biota sub-categories. Based on maximum rating.**			**No conservation importance; no sensitive taxa present**	**Slight conservation importance; a few taxa present**	**Moderate conservation importance; moderately sensitive taxa present**	**Very high conservation importance; highly sensitive taxa present**	**Extremely high conservation importance; very highly sensitive taxa present**
		Automated	Is the site in a protected area (Critical biodiversity area, Ecological support area, important fish area, National Freshwater Ecosystem Priority Area)	No to all of these				Yes, to one or more of these
		Automated	What is the Present Ecological State Category?	E/F	D	C	B	A
		Automated	What is the mean Ecological Importance Class?	Very low	Low	Moderate	High	Very high
		Automated	What is the Mean Ecological Sensitivity Class?	Very low	Low	Moderate	High	Very high
		Automated	What is the Ecological category (SASS only)?	E/F	D	C	B	A
		Automated	Are there endemic species?	Widespread (more than one Freshwater Ecoregion)	Regional endemic level 1 (endemic to a Freshwater Ecoregion (e.g. CFE), more than one primary catchment)	Regional endemic level 2 (endemic to one primary catchment)	Micro-endemic level 1 (<5 rivers, within one primary catchment)	Micro-endemic level 2 (1 river)
		Automated	Are there IUCN Red listed species?	No IUCN Red listed species present	No IUCN Red listed species present	One IUCN Red listed species present	Two IUCN Red listed species present	Two or more IUCN Red listed species present
		Automated	Are there thermally sensitive taxa?	No taxa present	Highly thermally tolerant taxa present	Moderately thermally tolerant taxa present	Moderately thermally sensitive taxa present	Highly thermally sensitive taxa present
		Automated	Are there oxygen sensitive taxa?	No taxa present				Taxa present

Component	Category	Generated	Descriptions/ questions	Rating				
				1	2	3	4	5
Overall severity			**Average of scores given for flow regime, physico-chemical, habitat and biota**					
Spatial scale			Extent of the impact scored according to spatial extent	Site	River reach	River	Regional/neighbouring areas (downstream within quaternary catchment)	National (impacting beyond secondary catchment or provinces)
Duration			Duration of the impact scored according to the length	One day to one week	One week to one month	One month to 1 year	1 year to 10 years	> 10 years
Consequence			**(Sum Resilience+ Severity+Spatial Scale+Duration)/4**					
Frequency of activity			Score frequency of activity; How often is the activity undertaken?	Annually or less	6 Monthly	Monthly	Weekly	Daily
Frequency of impact			Score frequency of impact; How often does the activity impact on the resource quality?	Almost never/almost impossible/>20%	Very seldom/highly unlikely/>40%	Infrequent/unlikely/seldom/>60%	Often/regularly/likely/possible/>80%	Daily/highly likely/definitely/>100%
Likelihood			**(Sum Frequency+Frequency Impact)/2**					
Significance			**Significance = Consequence X Likelihood**					
Risk Rating			Indicate the risk rating based on predetermined Risk Classes: Low Risk, Moderate Risk, High Risk, Very high Risk					

Appendix 5. An example of a Thermal Report Card

Overview



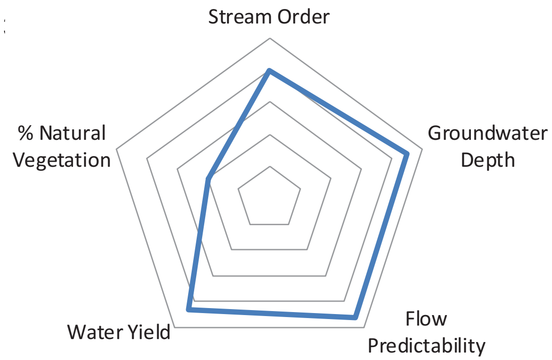
FBIS Site Code	G1EERS-JONKE
Site coordinates	XXXXXX XXXXXXX
Site description	Upstream of Witbrug bridge
River	Eerste River
Geomorphological zone	Mountain stream
Freshwater Ecoregion of the World	Cape Fold Ecoregion
Water Management Area	9-Berg Olifants
Sub Water Management Area	Greater Cape Town
River Management Unit	XXXX
Primary catchment	XXXX
Secondary catchment	XXXX
Tertiary catchment	XXXX
Quaternary catchment	XXXX
Quinary catchment	XXXX
SA Ecoregion Level 1	Cape Fold Mountains
SA Ecoregion Level 2	XXXX
Protected area	XXXX
Critical biodiversity area	XXXX
Ecological support area	XXXX
Important fish area	XXXX
National Freshwater Ecosystem Priority Area	XXXX

Köppen Climate Zone	
Hydrological Region	XXXX
Flow Regime Type	XXXX
DWS Hydrological gauging station (nearest)	XXXX
DWS Hydrological gauging station coordinates	XXXXXX XXXXXXX
DWS Water Quality station (nearest)	XXXX
DWS Water Quality station coordinates	XXXXXX XXXXXXX

Screening process

How resilient is the site to changes in water temperature?

Total Resilience Score = :

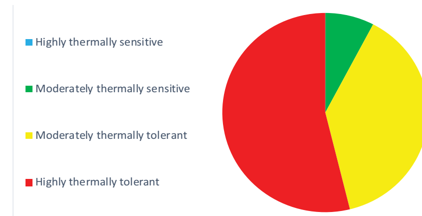


Are there other hydrological, physico-chemical (water quality) and habitat considerations that could magnify or diminish thermal impacts?

Flow regime	
Naturalized streamflow per WMA	571 million m³/a
Present Day streamflow per WMA	220 million m³/a
Present Day Mean Annual Runoff (MAR) as a percentage of Natural MAR	38.5%
Physico-chemistry (water quality)	
Dissolved oxygen concentration	< 5.0 mg/l
Turbidity	Opaque
Average inorganic nitrogen concentration	1.5 mg/l (Mesotrophic)
Average inorganic phosphorus concentration	0.01 mg/l (Mesotrophic)
Un-ionised ammonia (NH3) concentration	0.015 mg/l
Other chemicals present	Unknown
Potential for algal blooms	No
Potential for growth of invasive aquatic macrophytes	No
Habitat (geomorphology and riparian)	
Condition of instream habitat	Low
Condition of riparian habitat	Low
Effect on sediment processes	Low

How sensitive are the river organisms?

Protected area	No
Critical biodiversity areas	No
Ecological support area	No
Important fish area	No
National Freshwater Ecosystem Priority Area	No
Present Ecological State Category	D
Mean Ecological Importance Class	Low
Mean Ecological Sensitivity Class	Moderate
Ecological Category (SASS only)	C
Endemic species	None
IUCN Red List species	None
Macroinvertebrate Thermal Sensitivity Index	
Thermal Sensitivity Score	20
Number of Taxa	13
Average Thermal Sensitivity Score per Taxon	1.54
Are there species with specific thermal requirements?	No



Are there species with specific oxygen requirements?	No

Thermal Impact	Heated water from WWTW

Component	**Risk Rating**
Severity - flow regime	5
Severity - physico-chemistry	4
Severity - habitat	2
Severity - biota	3
Overall Severity	**3.5**
Consequence	**3.1**
Likelihood	**5**
Significance	**16**
Risk	**Moderate Risk**

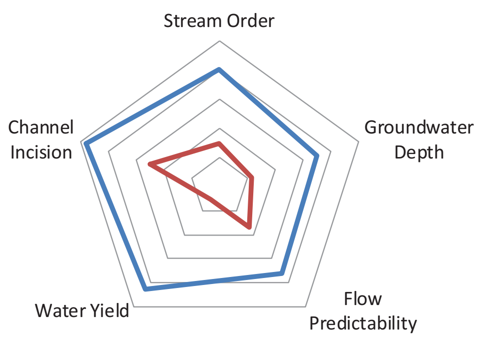
Evaluation process

Is there an existing reference thermograph for the site?	Yes / No
Is there Reference Water Temperature Data for the site?	Yes / No
Is there available Air Temperature Data	Yes / No
Is there modelled Water Temperature Data	Yes / No
Is the monitoring Site Water Temperature Data	Yes / No

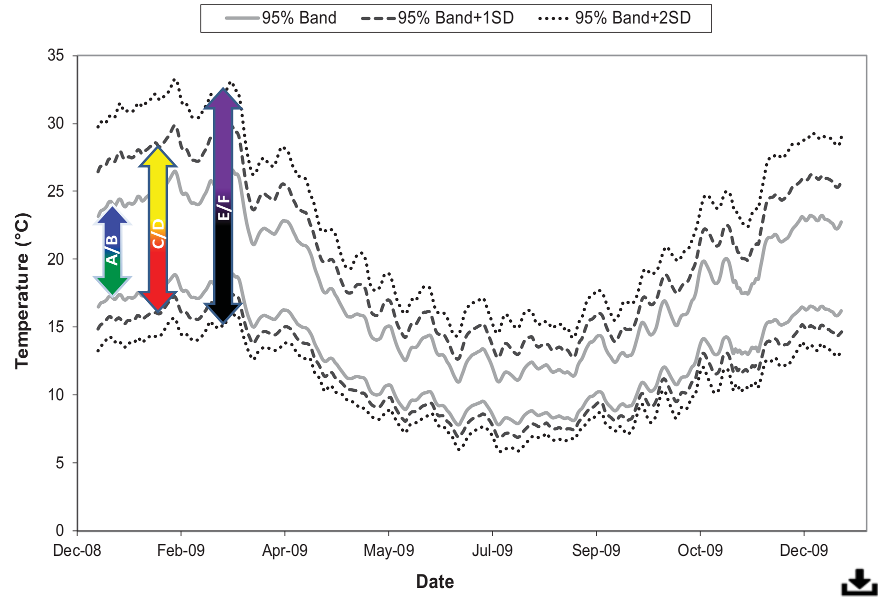
Indicators of Thermal Alteration (ITA) Metrics (* is outside reference range, red=hotter, blue=cooler)

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*

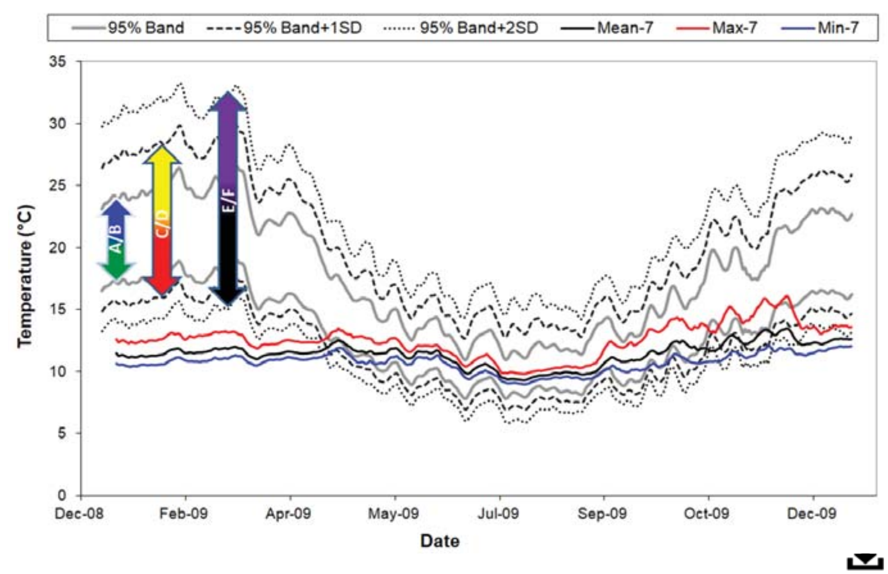
Model Accuracy Score = 1.88



Reference Thermograph



Monitoring site thermograph



Appendix 6. Logger installation tips

Suitable mounting sites include submerged tree roots (direct attachment using cable), bedrock or instream boulder attachment using Dyna bolts. Holes are drilled using a hammer drill. Field installation should take less than one hour, assuming a suitable site has already been found. Choice of logger depends on available technology and budget. Currently, it is recommended that Hobo TidbiT® v2 loggers (www.onsetcomp.com, and local supplier www.cwprice.co.za) should be housed in protective cases (Figures A1) made up according to the following specifications:

- 2mm x 50mm x 50mm steel cut into 100mm lengths.
- Two 6mm x 60mm stainless steel bolts (end thread only) and nuts inserted through either end of the steel casing in the shape of a plus to exclude large stones and prevent damage to the loggers. Holes drilled using 6.5mm drill bit.
- Logger attached internally using 4mm x 25mm stainless steel cap screws with nyloc nuts (tightened using 7mm spanner and 3mm Allen key).
- 3mm stainless steel cable attached via a loop to the steel housing and secured using 3mm Crosby clamps (7mm nuts). The stainless-steel cable is cut using a 900g ballpen hammer and 19 x 200m cold chisel.
- Free end of steel cable is attached to 25mm square lengths of 3mm x 25mm x 25mm angle iron. Angle iron is attached to suitable substrate using 8mm x 42mm Dyna bolts.

Figure A1 Hobo TidbiT® water temperature logger housing, showing side view with cable attached (left) and end view, illustrating placement of logger inside housing, and position of 6mm x 60mm stainless steel bolts (right)

Calibrations and laboratory testing may be undertaken using loggers in constant temperature baths. Here, water temperatures should be recorded at one-minute intervals using an alcohol thermometer (0.5 °C calibrations) and compared against logged water temperatures, using the following intervals:

- Ice bucket (0 °C)
- Boiling water (60 °C) cooled to 52 °C
- Cold water (16 °C)

Logger positioning within the river

Whilst the positioning of loggers is sometimes determined by the objectives of the monitoring programme, there are several recommendations related to the physical installation of the loggers:

- We generally recommend installing the logger during the low-flow period so that placement of the logger is likely to ensure it is covered by water during the low flow periods.
- We recommend that the logger be placed in a run within the thalwag of the river, where water is flowing during the low-flow period. If, however, the objective of a study requires a different positioning, such as to measure temperatures in pool biotopes, then the logger would be positioned, for example, in the pool.
- Always assess the risk of logger loss through high-flows. Often positioning a logger on the leeward side of a large boulder provides a degree of protection from fast flowing water and boulders or debris that might detach the logger from the rock.
- Always assess the risk of logger loss through theft, by selecting sites not frequently visited by humans, and which are ideally on private land or in a protected area. In all cases obtain the permission of the landowner.

Appendix 7. Generating water temperature data from air temperature data including published equations

Water temperature time series should ideally be based on observed data, but in their absence, can be simulated using a suitable water temperature model. No single model will be suitable for all of South Africa, but model accuracy can be improved by selecting site-specific models already published (Table A1), and which have been developed for upland and lowland zones.

Water temperature models are generally either process-based or statistical. Process-based models, which aim to simulate heat exchange processes, are generally data-intensive and appropriate for fine temporal resolution analyses. Conversely, statistical methods, while not necessarily simulating true cause-and-effect relationships, usually make use of fewer parameters based on readily obtainable surrogates. A generally linear relationship typically exists between air and water temperatures and assumes that the rate of change in heat storage in a river can be related to air temperature change. Air temperature is widely measured, which makes it convenient to use as a basis for predicting water temperatures. At high and low water temperatures, this essentially linear relationship breaks down, which may be compensated for using logistic models. Since high temperatures often coincide with low flow periods, process-based models, which consider the role of evaporative cooling may be appropriate in such cases, although such approaches are data-intensive.

While many water temperature models predict mean weekly or mean daily water temperatures, models appropriate for use by river ecologists should predict ecologically significant water temperature characteristics such as daily maxima. An obvious initial statistical approach relies on the generally linear relationship between air and water temperatures, inherent in which is that the data conform to the basic assumptions of linear regression. Simple linear regression models have been used for weekly to monthly water temperature predictions. However, a simple linear relationship between air and water temperatures may not always be adequate in describing water temperatures completely. Relationships may vary between catchments because of factors such as slope, aspect and seasonality of flows, which makes generally applicable models elusive. Furthermore, the instability of the relationship between air and water temperatures during the year implies that it is not one of true cause and effect. Thus, if necessary, parameters such as flow rates (and rainfall), relative humidity, water depth, and sediment load can be included into more complex water temperature models using multiple linear regressions, which have the advantage of allowing for simulating thermal time series under different scenarios and increasing the management utility value of such models.

Table A1. Generic regression models ($p < 0.001$) developed from Eastern and Western Cape temperature data, based on inputs of mean, minimum and maximum daily air temperature (AT, AT_{min}, AT_{max}), mean daily percentage relative humidity (RH), stream order (SO) and altitude (Alt). Numbers in brackets are degrees of freedom for the F-statistic.

Model Family	Metric	Equation	Mult. R^2
All data (simple)	Mean - F(2, 9878) = 8062	$WT = 0.46 + 0.70(AT) + 0.07(RH)$	0.62
	Min- F(2, 9878) = 8062	$WT = -2.34 + 0.72(AT) + 0.08(RH)$	0.61
	Max - F(2, 9878) = 8062	$WT = 3.97 + 0.69(AT) + 0.06(RH)$	0.47
All data (complex)	Mean - F(4, 9876) = 8062	$WT = -2.33 + 0.70(AT) + 0.08(RH) + 0.93(SO) + 0.001(Alt)$	0.69
	Min - F(3, 9877) = 8062	$WT = -4.33 + 0.71(AT) + 0.09(RH) + 0.87(SO)$	0.66
	Max - F(4, 9876) = 8062	$WT = 0.70(AT) + 0.07(RH) + 1.01(SO) + 0.001(Alt)$	0.53
Upland (simple)	Mean - F(2, 6493) = 4881	$WT = -5.07 + 0.68(AT) + 1.27\sqrt{RH}$	0.60
	Min - F(2, 6493) = 5204	$WT = -3.24 + 0.70(AT) + 0.09(RH)$	0.62
	Max - F(2, 6493) = 2313	$WT = 4.13 + 0.65(AT) + 0.06(RH)$	0.42
Upland (complex)	Mean - F(4,6491) = 3390	$WT = -5.32 + 0.73(AT) + 0.10(RH) + 1.50(SO) + 0.001(Alt)$	0.68
	Min - F(4,6491) = 3029	$WT = -6.57 + 0.73(AT) + 0.11(RH) + 1.02(SO) + 0.001(Alt)$	0.65
	Max - F(4,6491) = 1841	$WT = -3.5 + 0.74(AT) + 0.09(RH) + 2.12(SO) + 0.002(Alt)$	0.53
Lowland (simple)	Mean - F(2, 3382) = 3411	$WT = 1.87 + 0.71(AT) + 0.06(RH)$	0.67

Model Family	Metric	Equation	Mult. R^2
	Min - F(2, 3382) = 2503	$WT = -3.77 + 0.69(AT) + 1.08\sqrt{RH}$	0.60
	Max - F(2, 3382) = 2362	$WT = 3.48 + 0.73(AT) + 0.06(RH)$	0.58
	Mean - F(4, 3380) = 1875	$WT = 0.76 + 0.69(AT) + 0.06(RH) + 0.48(SO)$	0.69
Lowland (complex)	Min - F(6, 3378) = 1098	$WT = 3.89 + 0.60(AT) + 0.19(AT_{\min}) - 0.10(AT_{\max}) + 0.04(RH) + 0.37(SO) - 0.08\ln(Alt)$	0.66
	Max - F(4, 3380) = 1284	$WT = 2.19 + 0.72(AT) + 0.05(RH) + 0.48(SO) + 0.001(Alt)$	0.60

Appendix 8. Temperature metrics for disaggregating thermal time series (from Rivers-Moore et al. 2013a)

Annual descriptive statistics		Mean (MAT) + Standard Deviation of annual temperature Annual coefficient of Variability (% CV) Predictability Mean + Standard Deviation of daily range CV% of annual daily range Maximum daily range Mean of annual mimima, maxima Degree days (annual)
Group 1	Monthly magnitudes	January – December mean, minimum and maximum temperatures
Group 2	Magnitude and duration of annual extreme water temperature conditions	7-day mean 7, 30 & 90-day minima 7, 30 & 90-day maxima
Group 3	Frequency and duration (number of successive days of event above or below a threshold)	7-day mean threshold count & duration 7-day minimum threshold count & duration 7-day maximum threshold count & duration
Group 4	Timing - Julian date of maximum and minimum metrics (thermal triggers)	Date of onset of longest exceedance of mean threshold Date of onset of longest exceedance of minimum threshold Date of onset of longest exceedance of maximum threshold