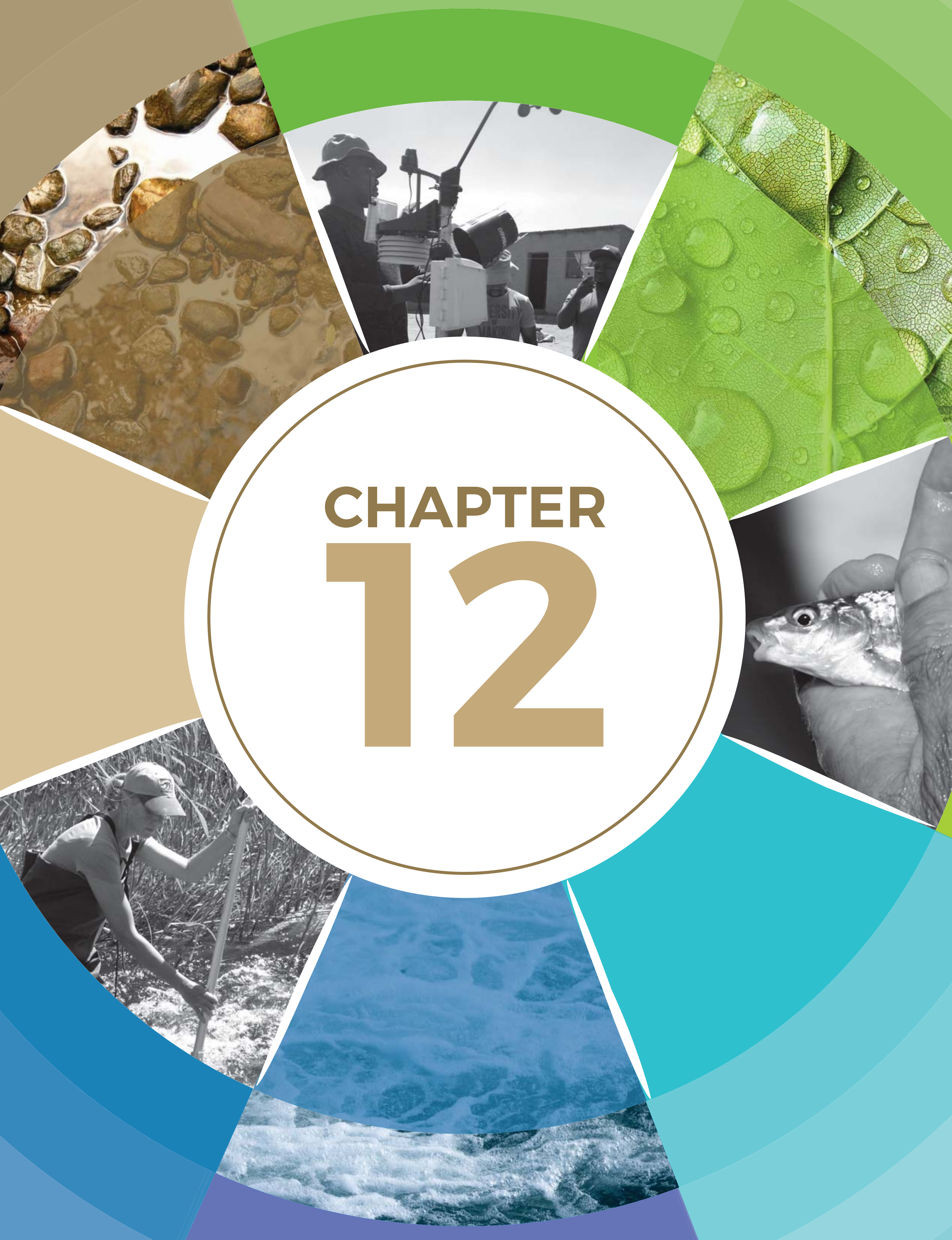
CHAPTER 12



CLIMATE CHANGE: ABIOTIC DRIVERS, IMPACT ON WATER RESOURCES AND ECOSYSTEMS, MITIGATION, AND MANAGEMENT OPTIONS

Helen Dallas, Nick Rivers-Moore and Mohammed Kajee

INTRODUCTION

"Take urgent action to combat climate change and its impacts" – this is the Sustainable Development Goal (SDG) 13 'Climate Action' of the 2030 Agenda (United Nations, 2018).

In 2002, the Water Research Commission (WRC) commenced a comprehensive research programme on climate-change impacts on water resources. This programme relied heavily on WRC water-related research on climate, atmosphere, ocean-atmosphere and hydrological modelling undertaken during the preceding 15 years. Later, the WRC produced the 'Research Portfolio on Climate Change for 2008-2013', a culmination of a discussion paper on current climate change research efforts in South Africa in relation to water, the national policy environment, and a national workshop (Green, 2008*). In this, priority topics and potential initiatives requiring water-sector participation were identified, including 1) refinement and communication of climate-change scenarios, projections, information, and data; 2) identification and quantification of impacts on water resources, including ecosystems and water quality; and 3) development and implementation of adaptation strategies and mitigation measures.

These topics later became themes in the Climate Change Lighthouse, namely impacts of, adaptations to and mitigation options regarding climate change (WRC, 2018) and have formed the recent focus of the WRC's strategy with respect to climate change in South Africa. Climate change research is relevant within all the WRC's key strategic areas, including Water Resources and Ecosystems, Water Utilisation in Agriculture, and Water Use and Waste Management; and climate change impacts ecosystems; agriculture, urban and industrial development, while its consequences have social and economic impacts.

South Africa is a water-stressed country with a mean annual precipitation (MAP) of 500 mm per annum (approximately 60% of the world average) (Zucchini and Nenadić, 2006). Climate changes include shifts in mean condition, variance and frequency of extremes of climatic variables, which result in changes in water quantity, especially in arid and semi-arid regions (Schulze, 2011*). Hydrologically, South Africa has a high-risk climate with very high year-to-year variability (e.g. a 10% change in rainfall can result in up to a 20–30% change in runoff) and a low conversion of rainfall to runoff (Stuart-Hill et al., 2011*). Runoff response to rainfall is also non-linear, with a larger proportion of rainfall being converted to runoff when a catchment is wetter, either because a region is in a high rainfall zone or because the soil water content is high as a result of previous rainfall (Schulze, 2011*). More than 50% of the water management areas in South Africa are currently in deficit, based on the ratio of annual withdrawals-to-availability (Alcamo et al., 2002), with southern Africa a 'critical region' of water stress (Alcamo and Henrichs, 2002). The ratio between MAP and mean annual potential evaporation is one way to quantify the relative dryness of the region, which varies from 1 in the east to >10 in the arid west (Schulze, 2011*). According to Kundzewicz et al. (2007), southern Africa is on a negative trajectory of climate-related changes, with precipitation, humidity and runoff decreasing, while the intensity and, in some case, frequency of droughts is increasing. The emphasis on climate related research, and the inclusion of climate change as one the WRC's lighthouses, is thus highly appropriate.

This chapter provides an overview of research related to climate change previously funded by the WRC. It focuses on Water Resources and Ecosystems, with specific focus on freshwater and, in particular, riverine, ecosystems. We discuss research on abiotic drivers of climate change, in particular climate-change-relevant research on precipitation, air temperature and evaporation in South Africa, and the development of climate change models for predicting trends in these drivers. We discuss research on the consequences of climate change on freshwater ecosystems, including those affecting water quantity, water quality, physical habitat and biological assemblages. Managing and mitigating the impacts of climate change are discussed and protocols and tools for managing water temperature in river ecosystems are provided.

Abiotic drivers of climate change

The primary drivers of climate change are changes in precipitation (areal or orographic rainfall; for example, changes in temporal or spatial patterns), shifts in precipitation patterns, increase in ambient air temperature, and increase in evaporation. Secondary impacts include an increase in the frequency of flooding and droughts, increase in sea-levels, and biological responses to the impacts of climate change (Green, 2008*).

Precipitation, air temperature and evaporation in South Africa

Rainfall and air temperature are the two elements of climate most important in determining the diversity and abundance of fauna and flora as well as a whole host of anthropogenic activities, including human settlement, economic development, and agriculture (McNeill et al., 1994*). As such, understanding how rainfall and temperature patterns have changed, are changing and will change under future climate change scenarios is imperative not only for human survival, but also for the survival of the diverse life forms that inhabit the planet. WRC-funded research on precipitation and air temperature in South Africa within the WRC dates back to the late 1980s, with studies focusing primarily on mapping mean annual rainfall statistics for the country (Dent et al., 1989*; Seed, 1992*; Mather et al., 1997*). The first WRC project on modelling present-day climatic conditions for southern Africa focused on developing a stochastic model for multiple climate variables (including temperature) at specific sites across South Africa (Brandao and Zucchini, 1990*). Following on from this, McNeill et al. (1994*) described a daily rainfall model for South Africa, which was calibrated at 2 550 sites across the country and captures all probalistic properties of the daily rainfall process at these sites. Jury et al. (1996*) identified mechanisms that govern in-season (15-40 day) variability of summer convection over the plateau of South Africa and its adjacent ocean areas, noting that in-season oscillations of rainfall are of significant amplitude over South Africa; while Jury (2002*) developed a statistical system to forecast summer rainfall over South Africa.

Daily and monthly rainfall datasets were consolidated and administered by the Computing Centre for Water Research early in 2000 and were a valuable resource for future studies. These rainfall datasets, together with data from the South African Weather Service, the Agricultural Research Council, the South African Sugar Association, and a large number of municipalities, private companies, and individuals; were used to develop a raster database of annual, monthly and daily rainfall for Southern Africa (Lynch, 2004*). This database consists of more than 300 million rainfall values for approximately 14 000 stations. Subsequent to these studies, a number of projects modelled various aspects of rainfall in South Africa, including extreme rainfall events (Joubert et al., 1999*; Smithers and Schulze, 2000a*; Lennard et al., 2013*), flood estimation (Smithers and Schulze, 2003*) and spatial interpolation and mapping of rainfall (Smithers and Schulze, 2000b*; Clothier and Pegram, 2002*; Pegram, 2003*; Schulze and Maharaj, 2004*; Pegram et al., 2005*).

In terms of air temperature mapping, Schulze and Maharaj (2004*) completed an important project that developed a gridded daily temperature database for South Africa, using methods to infill missing daily maximum and minimum temperature values for South Africa between 1950 and 1990. This database was one of South Africa's first comprehensive temperature time-series databases and acted as a data source for future projects as well as providing considerable methodological progress in dealing with and handling temperature time-series data (Schulze and Maharaj, 2004*; Schulze, 2011*; Dallas and Rivers-Moore, 2019a*, b*). Although freely-accessible South African rainfall and air temperature databases have excellent records from 1950 to 1999, most of the measurable climate change impacts have occurred in the past 20 years. While the abovementioned studies were not directly focused on precipitation and temperature as they relate to climate change, they were a valuable first step and formed the basis upon which several studies could assess long-term changes to South Africa's rainfall and temperature conditions and make projections for these variables into the future.

Limited projects have dealt with how climate change may affect evaporation rates in South Africa, providing scope for future research on this important component of the climatic system. The capacity for this already exists, through existing frameworks such as the Köppen climate classification for South Africa, which exists for both current and future climate conditions. To date only two studies have assessed evaporation rates across large parts of South Africa, although these are not in relation to climate change. McKenzie and Craig (1999*) developed methods for upscaling pan measurements to evaporation losses from rivers in the Orange River basin while Everson (1999*) sought to determine the evaporation rate from flowing water along the Orange River and to compare these results with pan evaporation data. This study importantly demonstrated that evaporation rates for entire river systems can be modelled using standard weather station and flow data (Everson, 1999). Beyond this, there are limited projects that have dealt with how climate change may impact evaporation in South Africa, providing scope for future research to focus on this important component of the climatic system.

Figure 1. The Orange River. (Credit: 123RF stock photo)

Climate change models for predicting trends

According to Ziervogel et al. (2014), South Africa arguably has the most advanced research, observation, and climate modelling programme on the African continent, with expertise situated across several universities and science councils, and several South African researchers leading and participating in international global-change research programs. Climate-change modelling is a complex topic so in this chapter we provide only some highlights. Global and regional climate change models predict likely trends in the magnitude and amplitude of event-driven systems, primarily rainfall and air temperature (Hewitson et al., 2004*; Hewitson and Crane, 2006; Lumsden et al., 2009). General circulation models (GCMs) are used for weather forecasting and those predicting climate change are known as global climate models (Hewitson et al., 2004*). GCM simulate the most important features of the climate, namely rainfall and air temperature. Uncertainties are inherent in CGM and predictions of rainfall intensity, frequency and spatial distribution have a lower confidence than for air temperature (Schulze, 2011*). CGMs are commonly downscaled to enable their outputs to be made relevant to regional- or local-scale climate change scenarios (Hewitson et al., 2005*; Hewitson and Crane, 2006). Regional models developed for South Africa demonstrate confidence in pattern changes at a sub-national scale, but lower confidence for the magnitude of change (Hewitson et al., 2005*; Hewitson and Crane, 2006).

Figure 2. South Africa is considered a water scarce country, with the majority of its river systems considered non-perennial. (Credit: 123RF stock photo)

The first WRC project to develop regional climate change projections for South Africa was conducted by Hewitson (1997*). This early model projected reductions of 10-15% in regional summer precipitation extending from the east coast to the central and northern regions of the country, and variable responses for air temperature. Projections were based on only one model and therefore considered to be very preliminary (Hewitson, 1997*). Subsequently, Hewitson (2001*) continued work on global and regional modelling to develop capacity on dynamic modelling for understanding climate change in South Africa, and in 2002, the WRC commissioned a more thorough regional modelling project on climate change and impacts on South African water resources (Schulze, 2005*). Empirical and a regional climate model (RCM) downscaling tools were used to project regional climate change scenarios for South Africa, using regional responses to large-scale circulation change simulated by three GCMs.

Key findings from this study, and supported by subsequent work of Hewitson et al. (2004*) and Hewitson and Crane (2006), included: a wetter escarpment in the east with excessive precipitation over the eastern parts of South Africa during the summertime; a reduction in rainfall over the western region of the country with a shorter winter season in the southwest and a slight increase in intensity of precipitation; and a drying in the far west of South Africa (Schulze, 2005*). Air temperature was projected to increase across the country, with maximum increases in the interior (Hewitson et al., 2005*).

More recently, Schulze (2011*) used five IPCC-approved GCMs (Bates et al., 2008) to statistically downscale rainfall projections for 2 600 rainfall stations and 400 temperature stations across South Africa. These climate change models predict that responses will not be uniform within South Africa and climate change is likely to impact most strongly on the western regions, with less of an impact as one moves eastwards. Dallas and Rivers-Moore (2014) summarised the responses of freshwater systems to rainfall and air temperature changes as predicted by the climate change models, with summer and winter rainfall regions given separately where relevant (Table 1). For example, January (summer) maximum temperature is projected to increase by 2–6 °C (Figure 4). Certain areas are likely to become 'winners' in light of certain projected changes, while other areas are likely to become 'losers' as more water-related stresses are experienced. 'Hotspots' of concern are the southwest of the country, the west coast and, to a lesser extent, the extreme north of South Africa (Stuart-Hill et al., 2011*).

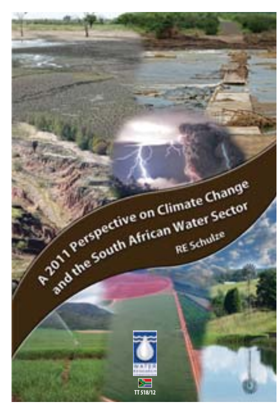


Figure 3. The 2011 study by Schulze used five IPCC-approved GCMs to statistically downscale rainfall projections for 2 600 rainfall stations and 400 temperature stations across South Africa.

Table 1: Responses of rainfall and air temperature for the summer and winter rainfall regions of South Africa as predicted by global climate change models (Hewitson and Crane, 2006; Lumsden et al., 2009; Schulze, 2011*). Published with permission by Dallas and Rivers-Moore (2014).

Predicted change in climatic factors	
Summer rainfall region (central, north, east)	Winter rainfall region (southwest)
Rainfall	
Increase in mean annual precipitation (MAP) of 40 mm to 80 mm per decade in the east, particularly the mountainous areas. Northern and eastern regions likely to become wetter in summer and autumn, especially over regions of steep topography around the escarpment and Drakensberg.	Decrease in MAP of 20 mm to 40 mm per decade. Shorter winter rainfall season, weaker winter pressure gradients, more summer rainfall from January onwards, especially inland and towards the east.
Increase in year-to-year absolute variability of MAP in the east (from 30% up to double).	Decrease in year-to-year absolute variability of annual precipitation.
Wetting trend of varying intensity and distribution, particularly in the east and transitional region. Drying trend in the middle and towards the end of the wet season (i.e. January, April) in northern areas.	Drying trend in the west, mainly in the middle of the rainy season (July) and towards the end of the rainy season (October). Mountainous regions predicted to be relatively stable, while coastal regions likely to become drier.
Greater interannual variability, intensifying in autumn.	Greater interannual variability, more irregular rainfall events.
Increase in intensity of rainfall events.	Increase in the frequency of extreme events, including drought as a result of the predicted poleward retreat of rain-bearing frontal systems.
Air temperature	
Into the IF mean annual temperatures are projected to increase by 1.5–2.5 °C along the coast and by 3.0–3.5 °C in the far interior. Into the MDF mean annual temperatures are projected to increase by 3.0–5.0 °C along the coast and by more than 6.0 °C in the interior. Interannual variability (as standard deviation of annual mean) of temperature is projected to increase by ~10% over much of South Africa, with increases in excess of 30% in the north. Variability in mountainous areas in the south and west is not projected to change (i.e. January, April). July (winter) minimum temperatures are projected to increase by a wider range from <4 °C to >6 °C, but with essentially an increasing south to north gradient from the coast to the interior.	
January (summer) maximum temperature is projected to increase by 2–4 °C.	January (summer) maximum temperature is projected to increase by 4–6 °C.
In KwaZulu-Natal, mean daily air temperature is likely to increase by approximately 2.5 °C.	Increase in days with hot, berg winds during December/January/February.

IF, intermediate future (2046–2065); MDF, more distant future (2081–2100)

Note: model predictions are more in agreement for temperature than for rainfall.

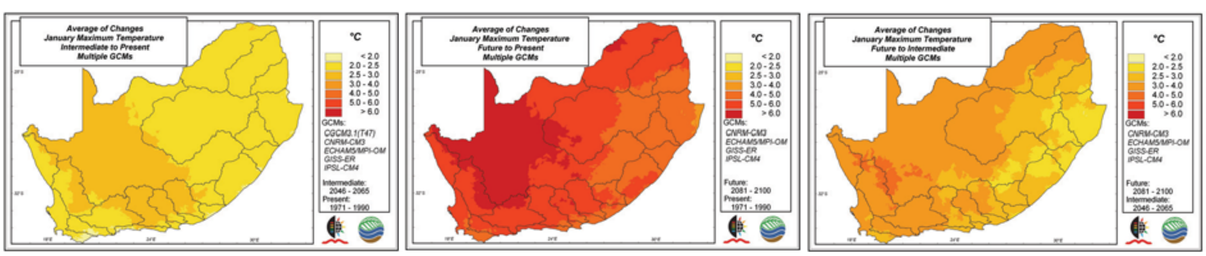


Figure 4: Average of changes (°C), using output from multiple GCMs, of means of daily maximum temperatures for January between the intermediate future and present (left), the more distant future and present (middle) and the more distant and intermediate future climate scenarios (right) From Schulze and Kunz (2011*), page 81.

Impact of climate change of water resources and ecosystems

Climate-change drivers directly affect the quantity of water in aquatic ecosystems by changing runoff patterns (e.g., mean values, flow variability, duration and timing), increasing the frequency and intensity of extreme events (floods and droughts), increasing water temperature and changing groundwater recharge rates (Dallas and Rivers-Moore, 2014). Stressors often act in synergistic ways with effects exacerbated through the interaction of two or more stressors such as the combined effect of reduced runoff and elevated water temperature. Climate change is likely to impact all aquatic ecosystems, including freshwaters (rivers and wetlands), estuaries and groundwater, with pronounced effects on inland freshwater ecosystems through altered precipitation, increased temperatures and more frequent or intense disturbance events (droughts, storms, floods). The impact of climate change on rainfall and catchment runoff is also likely to have a significant impact on estuarine functioning, which is strongly influenced by the magnitude and timing of freshwater runoff reaching them. Climate change affects groundwater levels, recharge rates and groundwater contribution to baseflow, although to date little research has been conducted on the future impact of climate change on groundwater resources in South Africa (Dennis et al., 2013*).

This section focuses on riverine ecosystems, while climate-related studies in other aquatic ecosystems, viz, cross reference wetland chapter, cross reference estuaries chapter and cross reference groundwater chapter, are discussed in the various related chapters. A paper on the ecological consequences of global climate change for freshwater ecosystems in South Africa (Dallas and Rivers-Moore, 2014) – the culmination of a workshop jointly funded by the WRC and World Wildlife Fund in 2009 – provided the basis for this section. The aims of that workshop were: to initiate dialogue between climate-change and freshwater experts; to improve our understanding of the likely consequences of climate change on freshwater ecosystems in South Africa; to document different forecasts that climate change will have on freshwater ecosystems with respect to water resources, the integrity of freshwater ecosystems, social and economy impacts; and to develop a planning framework for investigating possible adaption measures for the impacts of climate change on freshwater ecosystems (Dallas and Rivers-Moore, 2009a).

Freshwater ecosystems are amongst those most vulnerable to climate change (Bates et al., 2008). Observational records and climate projections provide abundant evidence that freshwater resources have the potential to be strongly impacted by climate change, with wide-ranging consequences for human societies and ecosystems (Bates et al., 2008). While historically studies on climate change have focused on terrestrial ecosystems, in the last decade attention has shifted to freshwater ecosystems (Filipe et al., 2013). This shift follows the recognition that freshwater ecosystems are vulnerable to climate change, are highly sensitive to climate change (Durance and Ormerod, 2007; Woodward et al., 2010) and that climate change is expected to worsen freshwater conditions, especially in Mediterranean regions (Filipe et al., 2013). Understanding the consequences of climate change for freshwater ecosystems requires consideration of effects related to water quantity, water quality, physical habitat and biological assemblages.

Impacts of climate change on riverine ecosystems – water quantity

The first major WRC-funded study focusing explicitly on climate change and impacts on South African water resources commenced in 2002 (Schulze, 2005*). Since this study, a substantial body of research has been undertaken in South Africa on the likely consequences of climate change on water resources, in particular rivers (Lumsden et al., 2009; Schulze, 2011*). A quinary catchment is a statistically defined region of uniform topography and relatively homogeneous hydrology falling within a quaternary catchment (Schulze, 2011*). Quinary catchments for South Africa, delineated by Maherry et al. (2013*) provide a valuable spatial unit for many subsequent studies, including the assessment of flow regime types to assist with setting regional water quantity requirements, and in particular, for determining the quantity of water needed in a river or stream (Rivers-Moore et al., 2016). Projected impacts of climate change on hydrological responses have been determined using the Agricultural Catchments Research Unit's (ACRU) process-based, daily time-step agro-hydrological modelling system (Schulze, 2011*). The first versions of ACRU were developed in the 1970s, coincident with the formation of the WRC. Since then, this model has been enhanced and expanded to the point where it is internationally recognised. It was often said tongue-in-cheek that ACRU "grew by degrees", and this is largely due to the funding of students by the WRC over the years.

The projected impacts of climate change on hydrological responses were determined using output from one to five GCMs, empirically downscaled to climate-station level and adjusted to the 5 838 quinary catchments. Predicted hydrological responses include changes in runoff patterns, in the frequency and intensity of extreme events, and in groundwater recharge rates for three 20-year climate time slices: the present (1971–1990), the intermediate future (2046–2065) and the more distant future (2081–2100) (Schulze, 2011*). Runoff is projected to increase over much of South Africa with the exception of the south-western Cape, which will have reduced streamflows especially in wet years, which will be less wet than currently (Schulze, 2011*; Dallas and Rivers-Moore, 2014). The reduction in streamflow would result in a change in perenniality (rivers) or permanence of inundation (wetlands), with perennial rivers becoming non-perennial and permanent wetlands becoming seasonal or temporary. In terms of drought, most parts of South Africa are likely to experience reduced frequency, duration and intensity of droughts, with the exception of the west coast and the north-west, which will experience marked increases in annual droughts (Schulze, 2011*; Dallas and Rivers-Moore, 2014). Floods and stormflow, i.e., the runoff of surface water from rainfall, are predicted to increase across South Africa, particularly in the central west where both magnitude and variability of stormflow will increase (Schulze, 2011*; Dallas and Rivers-Moore, 2014). Projected changes in groundwater recharge rates differ for each time slice and hydrological condition (dry year vs wet year conditions).

Impacts of climate change on riverine ecosystems – water quality

Higher water temperatures, increased precipitation intensity, and longer periods of low flows are projected to exacerbate many forms of water pollution, including thermal pollution, and increased concentrations of salt, sediments, nutrients, dissolved organic carbon, pathogens and pesticides (Bates et al., 2008). Climate-change drivers (rainfall and air temperature) primarily affect the quality of water in freshwater ecosystems by changing water temperature. Changes in water temperature may affect the solubility of oxygen and other gases, for example, decreasing the concentration of dissolved oxygen; altering the concentrations of inorganic nitrogen, phosphorus and un-ionised ammonia; modifying microbial activity; and changing chemical reaction rates and toxicity of chemicals such as atrazine, cadmium, cyanide, fluoride, lead, phenol, selenium, xylene, and zinc (Dallas and Day, 2004*; Dallas, 2008; Dallas and Rivers-Moore, 2019b*, 2021). Turbidity, nutrients, suspended sediments, metals, pesticides, and pathogens may also increase in response to more intense rainfall events, while in semi-arid and arid areas, salinity may increase as a result of increased evaporation from shallow ground and surface water (Dallas and Rivers-Moore, 2019b*, 2021). The quality of water in many South African rivers and wetlands is already widely compromised, and climatic drivers therefore act as additional stresses on these ecosystems (Dallas and Rivers-Moore, 2014). The effects of water quality variables on aquatic ecosystems have been widely documented (Dallas and Day, 2004*), with specific studies focusing on particular variables, including water temperature (Dallas, 2008).

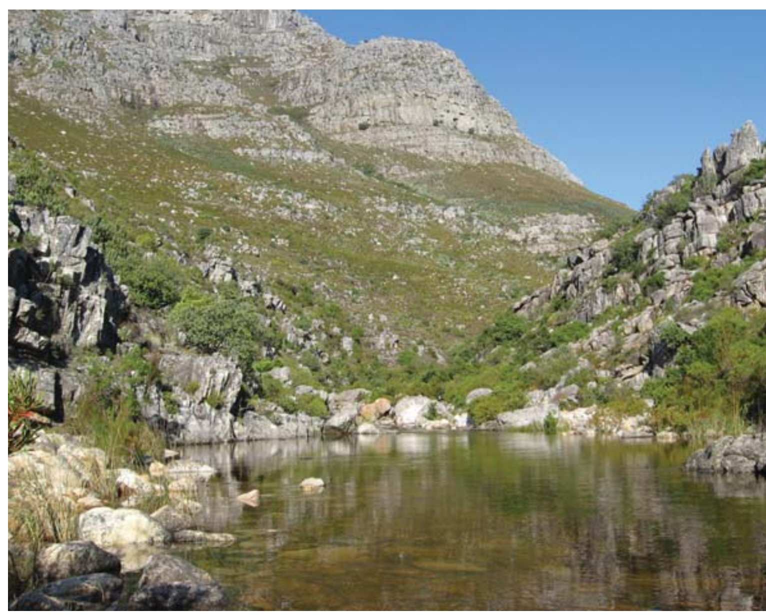


Figure 5. Wit River in the Western Cape . Environmental water temperature guidelines have been developed for South Africa's perennial rivers. (Credit: Helen Dallas/Water Wheel archives)

Early water temperature data relied on minimum/maximum thermometers that were usually checked on a monthly basis. These data were collected since it was recognised that fish community assemblages in the Sabie River were fundamentally structured around temperature preferences (Weeks et al., 1996*). With the advent of relatively cheap yet reliable electronic temperature logging devices, recording continuous temperature data became increasingly viable from the early 2000s. Locally, the WRC funded the development of miniaturised water temperature loggers (Harding and Jarvis, 2007*; 2010*), which since being patented in 2013, provide a potentially low-cost, local solution to water temperature monitoring in South Africa. Several WRC studies have focused on water temperature in rivers (Rivers-Moore et al., 2004*; 2008*; Dallas, 2009*; Dallas and Rivers-Moore, 2012a*; Dallas et al., 2015*; Dallas and Rivers-Moore 2019a*,b*) (Table 2), with the first water temperature loggers installed in 2001 on the Sabie River under the umbrella of the WRC-funded Kruger National Parks Rivers Research Programme (Rivers-Moore et al., 2004*).

That study provided some of the first longer-time continuous hourly measurements of water temperature over a two-year period. Since then, sub-daily (mostly hourly) water temperature has been logged approximately 200 sites around South Africa (Table 2). In addition, associated projects such as the Table Mountain Group Aquifer project (FCG, 2014a, b, c, d) and others have collected sub-daily water temperature data, together with flow data. The data generated from these studies provide an immeasurably valuable resource for examining thermal signatures of river systems around the country, and, in the absence of an official water temperature monitoring programme, present the only water temperature data available on South African rivers. For some studies, two-hourly air temperature data was also recorded to facilitate the development of air-water temperature models (Dallas and Rivers-Moore, 2012a*).

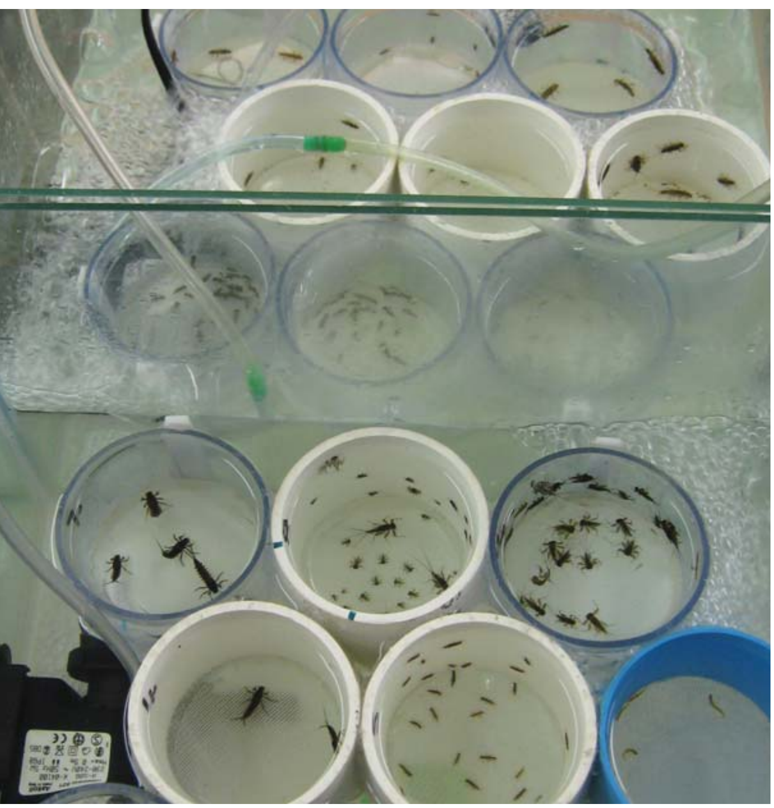


Figure 6. Thermal experiments to determine upper temperature limits undertaken to assess the impact of climate change on river systems. (Credit: Helen Dallas/Water Wheel archives)

Figure 7. The 2012 study by Dallas and Rivers-Moore made use of water temperature loggers housed in a protective metal casing. (Credit: Helen Dallas/Water Wheel archives)

Table 2: WRC funded studies, and in some cases associated theses, that collected water temperature using water temperature loggers.

Report	River(s)	Time period
RIVERS-MOORE NA, JEWITT GPW, WEEKS DC and O'KEEFFE JH (2004) Water temperature and fish distribution in the Sabie River system: Towards the development of an adaptive management tool. Water Research Commission Report No. 1065/1/04. Water Research Commission, Pretoria, South Africa.	Nine sites on the Sabie River, Mpumalanga.	2000-2002
PAXTON BR and KING JM (2009) The influence of hydraulics, hydrology and temperature on the distribution, habitat use and recruitment of threatened cyprinids in a Western Cape river, South Africa. Water Research Commission Report No. 1483/1/09. Water Research Commission Pretoria, South Africa.	One site on the Driehoeks River, Western Cape.	2004-2006
EWART-SMITH JL and KING JM (2012) The relationship between periphyton, flow and nutrient status in south-western Cape foothill rivers and the implications for management. Water Research Commission Report No. 1676/1/12. Water Research Commission, Pretoria, South Africa.	Two sites on the Berg River and one on the Molenaars River, Western Cape.	2007-2009
KETLEY Z (2009) Stream invertebrates and water temperature: Evaluating thermal tolerances in the Cape Floristic Region (South Africa) - implications of climate change. PhD thesis, University of Cape Town.	Six sites on Window Gorge stream, Kirstenbosch, Western Cape.	2008-2009
DALLAS HF and RIVERS-MOORE NA (2012a) Water temperatures and the Reserve. Water Research Commission Report No. 1799/1/12. Water Research Commission, Pretoria, South Africa.	88 sites on 56 rivers in the Western, Southern and Eastern Cape. Air temperature at 46 sites on 42 rivers.	2009-2010
FRESHWATER CONSULTING GROUP (FCG) (2014) Table Mountain Group Aquifer (TMGA) Ecological and Hydrogeological Monitoring project. Resource & Infrastructure Planning (Bulk Water), City of Cape Town.	Nine sites on seven rivers, Western Cape. Air temperature also recorded.	2011-present
DALLAS HF, RIVERS-MOORE NA, ROSS-GILLESPIE V, RAMULIFHO P and REIZENBERG J (2015) Adaptability and vulnerability of Riverine Biota to Climate Change – Developing Tools for Assessing Biological Effects. Water Research Commission Report No. 2182/1/15. Water Research Commission, Pretoria, South Africa.	18 sites on rivers in the Western Cape, Southern Cape, Eastern Cape, Mpumalanga and KwaZulu-Natal.	2013-2014
PAXTON BR, DOBINSON L, KLEYNHANS M and HOWARD G (2016) Developing an elementary tool for Ecological Reserve monitoring in South Africa's Freshwater Ecosystem Priority Areas (FEPAs): a pilot study in the Kouebokkeveld. Water Research Commission Report No. WRC Report No. 2340/1/16. Water Research Commission Pretoria, South Africa.	Two sites (Twee and Riet Rivers) in the Kouebokkeveld, Western Cape.	2013-2019
PAXTON BR (2021) Unpublished data. FRC Cape Critical Rivers Project: Saving Barrydale redfin.	Two sites on the Huis River, Barrydale, Western Cape.	2013-2015
PAXTON BR (2021) Unpublished data. FRC Cape Critical Rivers Project: Saving Sandfish.	Two sites on the Oorlogskloof River, Northern Cape.	2015-2017
EWART-SMITH JL, ROSS-GILLESPIE V and GRAINGER C (2017) The development and application of periphyton as indicators of flow and nutrient alterations for the management of water resources in South Africa. Water Research Commission Report No. TT 784/18. Water Research Commission, Pretoria, South Africa.	Two sites on the Mzunduzi River, two on the uMngeni River and one on the Hklatikhulu River, KwaZulu-Natal.	2014-2015
DALLAS HF, SHELTON S, PAXTON BR, WEYL O, REIZENBERG R, BLOY L and RIVERS-MOORE NA (2019) Assessing the effect of climate change on native and non-native freshwater fishes in the Cape Floristic Region, South Africa. Water Research Commission Report No. TT 801/19. Water Research Commission, Pretoria, South Africa.	Multiple sites (> 50) on the Amandel and Berg Rivers in the Western Cape.	2015-2016
REIZENBERG J, BLOY I, WEYL O, SHELTON J and DALLAS HF (2019) Variation in thermal tolerances of native freshwater fishes in South Africa's Cape Fold ecoregion: examining the east–west gradient in species' sensitivity to climate warming. J. Fish. Biol. 94 (10) 103-112.	Driehoeks, Rondegat, Amandel, Berg Rivers in the Western Cape and the Fernkloof River in the Eastern Cape.	2015-2017
RIVERS-MOORE NA and PALMER R (2017) Development of a predictive management tool for Orange River blackfly outbreaks. WRC Project No. K5/2459, Water Research Commission, Pretoria.	Nine sites along the middle and lower Orange River, Northern Cape.	2015-2016
OLSEN T, SHELTON SM and DALLAS HF (2021) Does thermal history influence thermal tolerance of the freshwater fish Galaxias zebratus in a global biodiversity hotspot? J. Therm. Biol. 97: 102890. doi.org/10.1016/j.jtherbio.2021.102890.	Eleven sites on six rivers (Liesbeek, Diep, Schusters, Silvermine, Admirals Kloof and Disa Rivers) on the Cape Peninsula, Western Cape.	October 2017 to April 2018
RAMULIFHO PA, FOORD S, and RIVERS-MOORE N (2019) Modelling flow and water temperature in the Luvuvhu catchment and their impact on macroinvertebrate assemblages. PhD Thesis, University of Venda, Thohoyandou, South Africa.	Ten sites on six rivers (Dzindi, Lutanandwa, Luvuvhu, Mutale, Mutshundudi, Tshirovha Rivers) in the Luvuvhu Catchment, Limpopo Province.	2016 to 2018

Report	River(s)	Time period
REIZENBERG J (2021) The Giant Redfin (Pseudobarbus skeltoni) and Climate Change: Assessing the effect of key physico-chemical parameters and biological traits on the distribution of an endangered native freshwater fish species in the Cape Fold Ecoregion. PhD thesis, University of Cape Town.	Multiple sites with 6 months data (> 50) and eight sites with one year data on Tierkloof River, and two sites on the Riviersonderend River, Western Cape.	2019-2020
Freshwater Research Centre (2021) Unpublished data. The Nature Conservancy Monitoring & Evaluation project.	Two sites (Du Toits and Riviersonderend Rivers), Western Cape	2019-2021
DALLAS H (2021) Unpublished data	Several rivers in the vicinity of Cape Town, including the Berg, Diep, Eerste, Elandspad, Molenaars, Rooielskloof, Silvermine, Skeleton Gorge, Window Gorge, Witte Rivers.	Variable periods within the years 2009-2020

Over the last two decades, using these thermal time series as primary data, ecological research has been undertaken in numerous river systems across South Africa (Rivers-Moore and Jewitt, 2004; Rivers-Moore et al., 2004*; 2005a; 2008*; Dallas, 2008; Dallas and Rivers-Moore, 2012a*; Dallas et al., 2015; Dallas and Rivers-Moore, 2019a*,b*, 2021; Dallas et al., 2019*), including thermal variability (Dallas and Rivers-Moore, 2011), development of air-water temperature models (Rivers-Moore and Lorentz, 2004; Rivers-Moore et al., 2005b; Dallas and Rivers-Moore, 2012a*; Rivers-Moore et al., 2012), generation of indicators of thermal alteration (ITA) and thermographs (Rivers-Moore et al., 2012; 2013a), creation of national maps and databases of thermal resilience and air-water model accuracy (Dallas and Rivers-Moore, 2019a*, b*), and indices for managing water temperature (Rivers-Moore et al., 2005a; 2016). Protocols and tools have been developed for establishing environmental water temperature guidelines and setting thermal targets (Rivers-Moore et al., 2013a; 2015; Dallas et al., 2015*; 2019*; Dallas and Rivers-Moore 2019a*, b*, 2021). These are discussed further in the section 'Managing water temperatures in South African rivers'.

Impacts of climate change on riverine ecosystems – physical habitat

Changes in the amount, intensity and seasonal distribution of rainfall affect channel geomorphology; lateral, longitudinal, and temporal connectivity; and aquatic habitat, through changes in runoff (Dallas and Rivers-Moore, 2014). While geomorphological studies in South Africa have not focused specifically on climate change (see chapter on rivers), observations elsewhere are likely to be applicable, with many effects similar to those already observed following the construction of impoundments and abstraction of water. Geomorphological changes from increased discharge may include, greater channel instability and sinuosity, and increased bank erosion, while decreased discharge may result in channel shrinkage, greater channel stability, vegetation encroachment, and sedimentation in side-channels (Dallas and Rivers-Moore, 2014). Loss of lateral, longitudinal and temporal connectivity can lead to isolation of populations, failed recruitment and local extinction; the maintenance of natural connectivity patterns is thus essential to the viability of populations of many riverine species and for maintaining instream integrity (Bunn and Arthington, 2002). Connectivity is typically reduced through flow regulation by dams and is often compounded by other structural modifications such as channelisation. Ecological processes in rivers are disrupted when upstream-downstream connectivity is broken (Rivers-Moore et al., 2016; Ramulifho et al., 2018). The development of a multi-metric connectivity index facilitates the quantification of river connectivity holistically (lateral, longitudinal and temporal components), providing a basis for identifying areas of vulnerability of aquatic biota to disturbances such as the effects of climate change using suitable scenario models (Dallas et al., 2015*; Rivers-Moore et al., 2016). In streams, flow is a major determinant of physical habitat, which in turn is a major determinant of biotic composition. Studies examining changes in physical habitat and biota, in particular changes in flow, include a study on fish (Paxton and King, 2009*) and aquatic invertebrates (Tharme, 2010), the latter where manipulated low flows resulted in consistent, marked declines in physical habitat availability for aquatic invertebrates. Regions predicted to have decreased flow are therefore likely to exhibit increased fragmentation of existing instream and riparian habitats, with resultant loss of habitat and connectivity.

Impacts of climate change on riverine ecosystems – biological assemblages

Research on understanding the physical nature of water temperature in river ecosystems, in particular ITAs and thermographs, has provided a landscape-scale framework for subsequent climate-related research focusing on biological responses of aquatic organisms, both at the individual and community level. Effects of changes in water temperature 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 (for example, blackfly species such as ***Simulium chutteri***), 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 (Rivers-Moore et al., 2004*; 2013b; 2014; Dallas and Rivers-Moore, 2014; Rivers-Moore and Palmer, 2017*). Biotic responses to climate change, and in particular water temperature, have been investigated experimentally for aquatic insects (Dallas and Ketley, 2011; Dallas and Ross-Gillespie, 2015; Dallas et al., 2015*; Dallas, 2016; Dallas and Rivers-Moore, 2018; Ross-Gillespie et al., 2018; Dallas et al., 2019*) and fish (Reizenberg et al., 2019; Olsen et al., 2021).

Figure 8. Blackfly larvae on the banks of the Orange River. (Credit: Nick Rivers-Moore/Water Wheel archives)

Achievements include the development and utilisation of laboratory methods for measuring thermal tolerance of aquatic insects (Dallas et al., 2015; Dallas, 2016; Dallas and Rivers-Moore, 2018) and fish (Reizenberg et al., 2019; Olsen et al., 2021), development of methods to measure sub-lethal thermal effects such as egg development (Dallas and Ross-Gillespie 2015; Ross-Gillespie et al., 2018) and thermal preference (Dallas et al., 2019*). Field surveys have been undertaken to examine individual species (Dallas and Rivers-Moore, 2012b; Ross-Gillespie, 2014) and community responses to changes in water temperature and flow (Eady et al., 2013; Dallas et al., 2015*; Shelton et al., 2018a, b). Species distribution and logistic regression models have been used to predict the impact of climate warming on native, non-native and pest species (Rivers-Moore et al., 2013b; Rivers-Moore et al., 2014; Dallas et al., 2019*).

Through this research it has become clear that there are distinct 'winners' and 'losers' in terms of biological responses to climate change and, in particular, climate warming. Upper thermal tolerance limits varied spatially and temporally, and thermal limits are strongly influenced by thermal history, i.e., ambient water temperature of the stream or river where the organism is living (Dallas et al., 2015*; Olsen et al., 2021), confirming that thermal guidelines need to be developed for both regional and local scales. For aquatic insects, life-history responses appear to be finely attuned to thermal regimes, while the hydrological regime was noted as a driver determining population size and mortality (Ross-Gillespie, 2014; Dallas et al., 2015*). Field studies of climate change often adopt the approach of examining relationships between species and temperature, or flow, and then scaling up those relationships to estimate changes in species distributions under different climate change scenarios, or modelling probabilities of occurrence or chronic thermal stress using, for example, logistic regression models. Species distribution models (SDMs) developed for native and non-native fish species in the Cape Fold Ecoregion (Dallas et al., 2019*; Shelton et al., In prep.) showed that the geographic ranges of native fish species are likely to become restricted to differing degrees. The SDMs provide a potentially valuable tool for achieving conservation objectives – particularly for identifying climate change refugia for species at risk – and can inform water resource management and river rehabilitation priorities, as well as long-term conservation planning (Dallas et al., 2017; 2019*).

For aquatic insects, probabilities of hatching and breeding success, plus population sizes and generation numbers per month, under current and projected 2°C warmer water temperature scenarios, were modelled using spreadsheet and logistic regression probability models. The results suggest that cold-adapted Gondwanaland relict species are likely to become increasingly vulnerable and range limited, whereas multivoltine pest species are likely to become more abundant under scenarios of increased water temperatures (Rivers-Moore et al., 2013b). The latter may have substantial economic fallout, as demonstrated by the projected economic losses resulting from the synergistic impacts of flow regulation and warmer water temperatures on pest blackfly outbreaks along the middle and lower Orange Rivers (Rivers-Moore and de Moor, 2020). It is important to reiterate that climate change is often an added stress to already over-allocated and stressed ecosystems, with over-abstraction, in particular, likely to interact with other climate change impacts to reduce flow and dissolved oxygen levels and raise water temperatures beyond a species' environmental tolerance limits (Dallas et al., 2019*).

Adapting to climate change

National responses to climate change should include adaptation, mitigation, technological development and research (Green, 2008*), and proactive strategies are needed at local and national level to deal with the impacts of climate change and drought on water resources (Mukheibir and Sparks, 2006*). Schulze (2011*) provided a comprehensive discussion on climate-proofing the South African water sector, with practical suggestions for adaptation to climate change. Since then, the WRC has funded various projects to investigate the adaptive capacity of small towns and communities in the Northern Cape province to climate variability, specifically drought (Mukheibir and Sparks, 2006*), to develop a water sector guide of the most relevant adaptation technologies and approaches to climate change over the short, medium and long term for local government institutions, especially municipalities in South Africa (Dube et al., 2016*); to engage with rural communities in planning for climate change adaptation at a local level (Hay and Hay, 2014*), and to develop a decision-support framework for an adaptive management strategy to assess and modify water services delivery and development plans of Water Boards (Hughes et al., 2014*). Each of these studies speaks to water resources in South Africa at multiple levels but since the focus of this chapter is on riverine ecosystems, we discuss these in more detail below.

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

Figure 9. Climate resilience can be strengthened through services provided by healthy ecosystems. (Credit: 123RF/ Stock photo)

Managing and mitigating the impacts of climate change on water resources

There is consensus that, other than mitigating greenhouse gas emissions, the most effective way to address the effects of climate change on ecological systems is to focus on building ecological resilience through promoting adaptation of species and ecosystems to climate change impacts (Wise et al., 2014). Resilience in an ecological context reflects the capacity of natural systems to withstand and recover from environmental change and thus persist into the future. Systems that are more resilient are better able to adapt to changes in climate and ecosystem resilience is key to reducing the consequences of global climate change on aquatic ecosystems (Dallas and Rivers-Moore, 2014). Recently, Rivers-Moore and Dallas (In prep.) developed a database of variables likely to indicate riverscape resilience to thermal stress. Resilience of a river is likely to be affected by variables such as stream order, groundwater depth, flow predictability, water yield (i.e., precipitation minus evaporation) and catchment transformation. The resilience ratings for each variable are summed to generate a Total Resilience Score for each sub-catchment and used to generate a map of system resilience to thermal stress for South Africa. Identifying resilience hotspots in rivers enables targeted conservation action when funding is limited and defining relative ecosystem resilience is important for evaluating the potential consequences of climate change on aquatic ecosystems.

Realistically, very little can be done directly to mitigate impacts on water temperature, and the most practical approach is to mitigate 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. To enhance the resilience of freshwater ecosystems, specific, proactive restoration, rehabilitation, and management actions are advocated (Dallas and Rivers-Moore, 2014).

Ways to promote ecosystem resilience include, for example, maintaining environmental flows, restoring instream, riparian and wetland habitat, restoring and maintaining connectivity within river networks, and recognising the link between catchment condition and freshwater ecosystem health (Dallas and Rivers-Moore, 2014).

Managing water temperatures in South African rivers

Effective management of water temperature requires an understanding of the thermal dynamics and biotic responses to changes in water temperature. The establishment of thermal guidelines that adequately protect aquatic ecosystems and their biota is dependent on an understanding of a river's thermal signature and the vulnerability of its biota to changes in water temperature (Dallas et al., 2015*). Over the last decade and a half, research on water temperature, including the biotic responses of aquatic organisms to climate warming in particular, have substantially increased our understanding of thermal signatures of rivers, and the sensitivity and vulnerability of the biota living in these rivers. Most recently, Dallas and Rivers-Moore (2019*, b*, 2021) translated this thermal research on South African rivers into a protocol for practitioners and decision-makers responsible for managing water temperature and protecting our river ecosystems. Resources include tabulated reviews of key thermal impacts and their prevalence in South African rivers, and of the biological effects of changes in water temperature on river organisms.

National-scale tools include a spatial framework within which air-water temperature models are applied in relation to national maps of air temperature-water temperature model accuracy and choice of upland versus lowland models, and a national map of system resilience. Both the system resilience and air temperature-water temperature model accuracy maps include an underlying database of variables likely to indicate system resilience and model accuracy. These data form the basis for developing reference thermographs (Figure 10) which reflect one or more thermally homogenous sites using hourly water temperature data and provide a natural range of variability using a thermal confidence envelope. Other innovative tools have been developed for generating thermal metrics and thermographs, and for generating a Thermal Sensitivity Index and identifying thermally sensitive taxa. A protocol for collecting water temperature data, including recommendations on selecting appropriate water temperature loggers, building logger housings and on-site installation methods, has been developed. The protocol developed for establishing environmental water temperature guidelines and setting water temperature targets for perennial rivers in South Africa includes a screening process to assess thermal risk; and an evaluation process to assess thermal change based on deviation from reference or expected thermal conditions (Dallas and Rivers-Moore, 2019a*, b*, 2021).

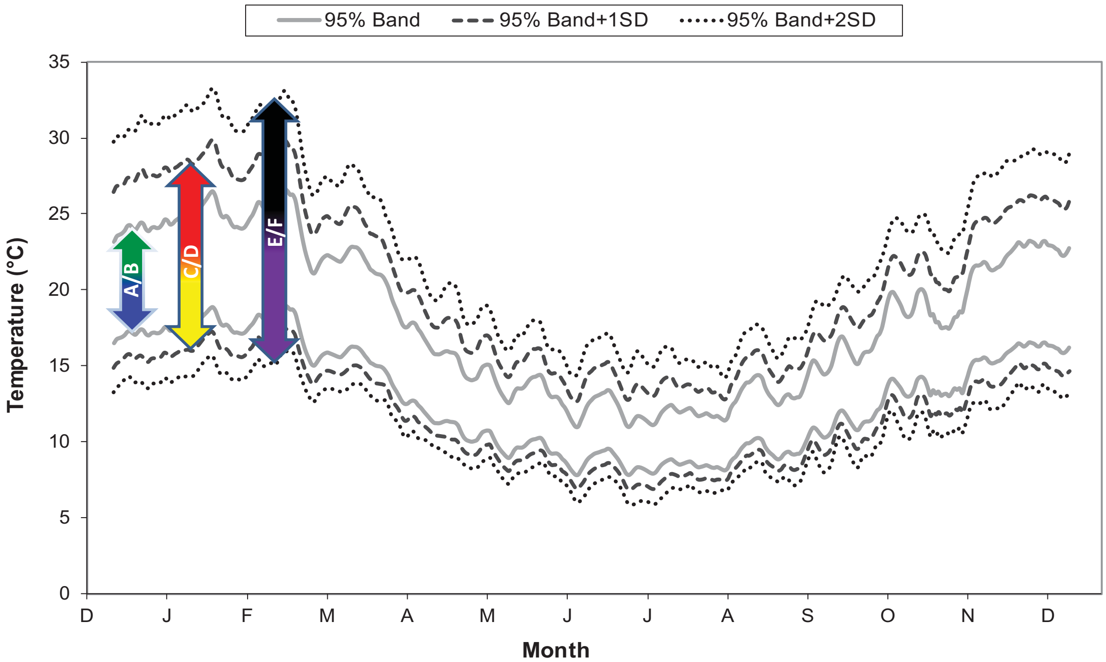


Figure 10. Reference thermograph indicating a reference condition thermal envelope plus one and two standard deviations (Dallas and Rivers-Moore, 2019b*, 2021). The associated Ecological Category (Kleynhans and Louw, 2007*) for each is indicated.

Conclusions and the way forward

Substantial advances have been made in climate-related research in South Africa over the last 20 years, with much of it funded by the WRC. Our understanding of the abiotic drivers of climate change and the projected responses of these key variables to climate change have grown exponentially over the last two decades. This understanding is critical, as the timing is commensurate with the growing climate-change-induced crisis particularly affecting freshwater ecosystems.

While uncertainties will always remain when it comes to models and modelling, the capacity and knowledge of the individuals and research groups involved in climate change modelling in South Africa has advanced considerably since 1990. Similarly, the knowledge of researchers focusing on water temperature in riverine ecosystems has grown enormously and has been expanded to numerous students through the life of the WRC-funded thermal and climate-change projects. Early WRC-funded work such as the Kruger National Park Rivers Research Programme initiated in 1988 (Breen et al., 2000*), identified water temperature as a key driver in ecosystems, which led to the initial study of biotic responses to water temperature and flow undertaken on the Sabie River in the early 2000s (Rivers-Moore et al., 2004*). The foresight of former WRC research manager, Dr Steve Mitchell, in 2005 resulted in the funding of three thermal consultancies (Harding and Jarvis, 2007*; Rivers-Moore et al., 2008*; Dallas, 2009*) with each researcher focusing on different aspects of water-temperature-related research. This culminated in the writing of the Terms of Reference for a long-term temperature programme that incorporated three broad themes: monitoring and modelling, biological responses, and management. The subsequent collaborative research project (2008-2011, Dallas and Rivers Moore, 2012a*) launched the comprehensive programme on water temperature in river ecosystems. Follow-on projects (Dallas et al., 2015*; 2019*; Dallas and Rivers Moore, 2019a*, b*, 2021) built on this foundational research such that laboratory, field and modelling studies greatly increased our understanding of water temperature and the ecological consequences of climate change on aquatic organisms and ecosystems. Translation of this research into innovative protocols and tools for managing water temperature in riverine ecosystems, and in particular for setting environmental water temperatures and thermal targets, has always been a priority for the researchers. The knowledge generated supports the uptake of research into water resource protection, conserving planning (Ramulifho et al., 2018) and policy (Bragg et al., 2017). Bridging the gap between scientific research and resource management, although challenging, is crucial. Further action is recommended to encourage use of the protocols and tools across the various water resource, biodiversity and conservation sectors.

Several gaps or needs have been identified during the development of this chapter. Firstly, long-term data are inherently valuable for evaluating the effects of climate change on aquatic ecosystems. What criteria should be used for strategically selecting sites to serve as sentinel sites for evaluating the potential impacts of climate change? How can monitoring of these sites be integrated into existing institutional business plans in the future and what alternative monitoring actions can be incorporated? The rollout of a national water temperature monitoring programme was identified as a need strongly endorsed by all end-users and stakeholders involved in the participation process of Dallas and Rivers-Moore (2019a*, b*, 2021). This programme 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.

Secondly, the automation of the processes developed in Dallas and Rivers-Moore (2019a*, b*) into a relevant information system that streamlines the input and output of data required for managing water temperature and setting thermal targets, was recognised as an important requirement to end-users. This includes the automation of the analysis of water temperature time series data into thermal metrics and thermographs to provide thermal signatures for a river. Automation of these processes will encourage the collection of water temperature data across a large segment of water resource practitioners and allow for the mobilisation of existing water temperature data collected by WRC project team members and other researchers in South Africa. While aspects of this are currently being incorporated in the Freshwater Biodiversity Information System (FBIS) (Dallas et al., 2021) further funding is required to mobilise thermal and associated biodiversity data in South Africa.

Thirdly, research on potential range shifts of aquatic biota, and how these can be met in relation to river connectivity, needs to be extended. Such information should, in turn inform freshwater conservation planning initiatives (such as the WRC-funded National Freshwater Ecosystem Protected Areas) to understand how effective current reserve networks will be in conserving species in the future.

Lastly, whilst the importance of groundwater in rivers and thermal buffering properties of groundwater is well recognised, the potential consequences of groundwater abstraction on water temperatures in rivers that are largely groundwater dependent is not yet fully understood. A study focusing on this aspect would be beneficial and improve our understanding of the links between surface water, groundwater, water temperature and biological consequences. In particular, managing groundwater protection and utilisation, groundwater recharge dynamics under climate change, and artificial recharge of aquifers as an adaptation measure, should be investigated.

Water and freshwater ecosystems are an integral component of three Sustainable Development Goals, 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. The Water Research Commission has been instrumental in developing institutional and individual capacity and generating knowledge on climate change and freshwater ecosystems in South Africa.

Acknowledgments

The authors are enormously grateful to the many students and research collaborators with whom they have worked over the last two decades of climate change and thermal research. The support of the Water Research Commission has been instrumental in growing our understanding of climate change, especially from the Water Resources and Ecosystems perspective and we gratefully acknowledge the research managers who have supported our projects (Dr Steve Mitchell; Mr Bonani Madikizela; Dr Brilliant Petja). In addition, a whole cohort of researchers have developed capacity and experience through the support of the Water Research Commission.