

Methodological Approaches to Assessing Eco-Hydrological Responses to Climate Change in South Africa

Report to the
Water Research Commission

by

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PREAMBLE

There has been growing concern that over the past few decades the phenomenon of climate change is already manifesting itself at the global scale and will continue to do so, initially at an accelerating rate. This has been observed in measurements of, *inter alia*, atmospheric CO₂ concentrations increasing from 280 parts per million (ppm) since the dawn of the Industrial Revolution to approximately 385 ppm at present, and also in global temperature records, with global mean surface air temperatures having increased by between 0.2 and 0.6 °C since the late 19th century. There is apprehension about climate change and, in particular, how it will manifest itself at the regional or local scale. This is largely because the tools to understand the risks (from more than 2-3 models of the future) posed at the regional scale (requiring simulations at finer spatial scales) were not available until recently. Even though improvements in the available tools and technology now exist, the translation of the projected climate changes into impacts on water and agriculture remain to be estimated. Major concerns surround the concept of increasing temperatures and associated shifts in precipitation attributes and patterns, which are likely to result in significant changes in water quantity and quality. The evidence for potential large scale climatic change is now sufficiently strong to justify further investigations not only of the causes, but particularly of its consequences in a variety of environments. Aquatic ecosystems are anticipated to respond to climate change both thermally and hydrologically. Many aquatic ecosystems are vital components in the landscape and are generally excellent candidates for research on global climate change.

Climate is one of the most important extrinsic drivers which determine hydrological regimes (i.e. the quantity and temporal distribution of streamflow). Even relatively subtle regional shifts in climate may alter not only the quantity of runoff, but also its variability and timing. Because ecological processes are regulated by the quantity and the temporal distribution of streamflows, major climate change-driven alterations in hydrological regimes are likely to result in modifications of freshwater ecosystem structure and function. Essentially, ecological responses will depend on the magnitude, direction, rate and spatial extent of any climatic change.

In South Africa there is a need to gain an insight into how projected climate change could impact on aquatic systems. To date South African research has been focussed on the primary impacts of climate change on hydrological responses. The research conducted in this component of the project, as decided upon by the project's Reference Group, aims at investigating effects of climate change on second (i.e. higher) order impacts, viz. ecological flow indicators and water temperature parameters. The research is focussed on scientific techniques and methods.

In order to achieve this goal, the downscaled climate output from the ECHAM5/MPI-OM General Circulation Model (GCM) is used as an input into the daily time step *ACRU* hydrological model in order to simulate the impacts of climate change, as projected by this particular GCM, on the selected eco-hydrological indicators at a fine spatial scale.

The report is divided into fifteen chapters. **Chapter 1** describes how the downscaled climate scenarios were developed, the state of current knowledge with respect to the climate system and how it may evolve, as well as the context within which these climate scenarios should be

assessed. **Chapters 2-15** deal with the hydrological modelling and derivation of ecological parameters. **Chapters 2 and 3** focus on aquatic ecosystems and ecological indicators within the context of climate change by exploring broad concepts surrounding the impacts of climate change on these systems. In **Chapters 3 and 4** flow and water temperature related parameters are proposed to assess the impacts of projected climate change. **Chapter 4** also includes a review of the relevant literature regarding the methods and models used estimate water temperature in lotic systems, while methods on computing water temperature are outlined in **Chapter 10**. In **Chapter 5** a description of the case study catchment for water temperature studies, viz. the Thukela Catchment, is given while **Chapter 6** focuses on scale issues surrounding the techniques of modelling and mapping of eco-hydrological indicators. This chapter introduces the concept of sub-delineating Quaternary Catchments into smaller and more homogenous Quinary Catchments. **Chapters 7, 8 and 9** summarise the relevant databases, models and techniques used in this project to assess the projected impacts of climate change on the selected eco-hydrological indicators. In **Chapter 11** an evaluation is presented of potential changes in hydrologically relevant statistics of rainfall in southern Africa under conditions of climate change. The modelling results for different magnitudes and durations of flow events, which had been selected for southern Africa in **Chapter 3**, are presented in **Chapter 12**. The results are presented by means of maps at the scale of Quinary Catchments. The results of the water temperature analysis for the Thukela Catchment are presented in **Chapter 13**, again by means of maps, while in **Chapter 14** time series graphs are used to describe water temperature parameters for 15 selected Quinary Catchments. A revisit of the project aims, a summary of findings and recommendations for future research, are provided in **Chapter 15**.

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EXECUTIVE SUMMARY

Background and Motivation

There is clear and compelling evidence that human-induced climate change is occurring, and this has already been identified in the historical record. This change is long term and accelerating, and the decades to come will place ever-increasing stress on natural and societal resources. In particular, it is the higher order impacts, i.e. the combinatory effects of changes in the attributes of both the large scale and regional scale forcings that are of primary concern at the regional scale. Effective adaptation and policy responses are predicated on a clear understanding of these issues.

Global Climate Models (GCMs) are the principal tools to project future changes in the climate system, yet at the same time GCMs have poor skill in resolving the regional scale details required to assess the local impacts. Robust tools to translate GCM projections to the local scale have been developed at the University of Cape Town over the past decade, and have matured to the point that they are at the forefront of such work internationally. Such scenarios are a necessary and essential foundation for *any* climate change impacts research. Nonetheless, whilst these tools are now generating local scale climate change scenarios, there remains a need to refine the products through tailoring for specific impact sectors.

Given the development of appropriate scenarios, two specific issues remain. First, what are the higher-order impacts to the primary climate system change? This issue reflects the fact that impacts are not solely a function of the primary forcing (the primary forcing may, on the face of it, seem inconsequential); rather impacts are a response to the combinatory nature of the forcing. For example; a reduction in the number of raindays, an increase in rainfall intensity and minimum temperature, and a shift in the diurnal cycle of precipitation, together would have a far greater impact on, say, water quality and nutrient cycling than would perhaps be suggested by considering simply the mean seasonal change of one variable.

It is only by appropriately assessing these attributes of the regional climate change forcing that one is in a position to credibly address the nature of the higher order impacts, be they nutrient cycling or any other ecological attribute. Addressing these impacts should then be approached by first assessing the sensitivity and critical thresholds of the relevant secondary impacts sectors to characteristics of change in the primary forcing, followed by using tailored change projections to highlight the particular elements of the change identified in the initial sensitivity assessment. These insights form the foundation for further action. Most important in this regard is to identify and facilitate research activities that focus on the key uncertainties and vulnerabilities in the knowledge base. This project seeks to set in place a framework for action and identify these key uncertainties in the current knowledge base.

Objectives of the Project

In order to address the needs as identified, a series of objectives were established for this project that explore the relationships between higher order responses of the coupled climate system and the local scale secondary responses in order to support the assessment of the aquatic

ecosystem, and for consideration in future development of policy responses and coping strategies that may lead to a strategic framework for adaptation, policy development, and resource management. The overall objectives of this project may be summarised as:

Objective 1: To generate likely scenarios for the primary and higher order impacts of climate change on water resources in South Africa, in order to support the development of policy responses and coping strategies.

Objective 2: To identify specific areas for future research, in order to:

- refine predictions related to the likely scenarios;
- enable the effects of possible policy responses to be evaluated with a reasonable degree of confidence;
- maintain capacity in southern Africa to update and refine scenarios and trajectories on an ongoing basis, in order to support refinement and further development of policy responses and coping strategies.

Objective 3: To identify specific aspects of water resources which should be addressed in long term monitoring programmes, in order to provide information and feedback on

- rates of change and possible thresholds of change;
- effects of policy and implementation of coping strategies.

Summary of Project Results

This project has set in place the necessary framework within which climate change and its secondary impacts on water resources can be evaluated and iterated in the future. By combining state-of-the-art climate change scenarios with a similar state-of-the-art agrohydrological model we have produced information on what climate change may imply for selected water sensitive sectors at a high spatial resolution for the whole of South Africa. This process has, in turn, enabled estimates of the secondary impacts of climate change as well as highlighting many important research agendas for the future. In particular from a climate modelling perspective:

- A statistical downscaling technique was used which allows daily time series of key climate variables for hydrology to be generated from observations and GCM data. This technique allows many GCMs to be downscaled and therefore a wide range of possible future climates to be sampled.
- Whilst this allows the first order response of the climate (i.e. rainfall and temperature) to be better understood, further work is required to understand how local feedbacks, such as those related to the land surface (land use change), regional ocean currents, populations and natural vegetation, alter these first order responses.
- Estimates of daily rainfall, minimum and maximum temperatures have been downscaled for 3000+ climate stations across South Africa, for 9 GCMs under an assumed A2 SRES scenario (all used as part of the IPCC 4th assessment report). This has been completed for the three periods, viz. 1960-2000, 2046-2065 and 2081-2100.

- Daily rainfall grids at 0.25° resolution have been produced for the same 9 GCMs and 3 periods. These data represent the most comprehensive range of downscaled models for South Africa.

Additionally the project has developed methodologies and, with those, generated a considerable body of new scientific results and recommendations from an eco-hydrological perspective. These are summarised below:

- The spatial scale at which the local hydrology has, to date, been modelled was identified as frequently being too heterogeneous, resulting in a further altitude based subdivision of existing Quaternary Catchments into 5 838 hydrologically more homogeneous response zones at Quinary Catchments level covering RSA, Lesotho and Swaziland. This allows, for example, the distinctions between higher upland / mountainous areas, a mid-catchment zone and lower riparian zones within a Quaternary, each of which have different characteristics with respect to hydrology and land use.
- The ECHAM5 GCM was used as a 'middle-of-the-road' GCM in terms of its output being between the wetter and drier models in the range of downscaled models. This was necessary as only this model was able to be coupled to the hydrological model within the lifetime of this project. It is, however, important to understand that ideally output from all available GCMs should be used before robust messages of change can be made.
- In an assessment of impacts of climate change on eco-hydrological flow indicators over South Africa, it was necessary to analyse a small subset of the 67 available hydrological indicators. Results indicate individual subcatchment runoff and accumulated streamflows to increase over the eastern parts of southern Africa by the intermediate future from 2046-2065, given the climate simulated by the ECHAM5 GCM. Decreases become apparent further west with this zone shifting westward by the more distant future from 2081-2100.
- Minimum flow durations are simulated to decrease in the Western Cape by 2046-2065 as are maximum flow durations by 2081-2100. Elsewhere these durations are simulated to increase, given the output from the ECHAM5 climate model.
- New water temperature indicators were developed for the Thukela Catchment, as primary indicators of water quality, and these represent the first attempt in South Africa at doing this under conditions of climate change.
- Consistent with the wider changes noted earlier, the Thukela Catchment is simulated to have increases in accumulated streamflows, as well as in water temperatures, and more so during the more distant future period than during the intermediate future. Again, these results are the response to one GCM climate model's output.
- Time series of individual Quinary Catchments indicate an increase in the variability of mean air temperature, runoff and accumulated streamflow over time.
- The mixed water temperature varies between the three Quinaries within each Quaternary catchment as a result of differences in hydrological responses because of variations in altitude.

Referring back to the primary objectives of the project these results suggest the following:

- The first objective of the project, viz. to ***generate likely scenarios for the primary and higher order impacts of climate change on water resources in South Africa, in order to support the development of policy responses and coping strategies*** was partially met,

though it should be noted that the majority of the work in achieving this objective has certainly been completed. The most difficult aspect was the coupling of the downscaled climate and hydrological models, which in the course of this project could be completed only for the ECHAM5 GCM. The remaining GCMs (additional to the ECHAM5 model) need to be run through the modelling framework before policy responses and coping strategies can be assessed;

- The second objective of the project, viz. to ***refine climate projections for the future in order to enable the effects of possible policy responses to be evaluated with a reasonable degree of confidence***, was completed successfully and some of the suggestions for further work are given below. In particular, through this project, projections of likely climate change have been refined. However, further work is required before policy responses can be evaluated, and in building / maintaining the capacity to further refine scenarios and reassess the impacts and effects on policy has been maintained within South Africa.
- The project has met most of the requirements of Objective 3, viz. to ***identify specific aspects of water resources which should be addressed in long term monitoring programmes, in order to provide information and feedback on rates of change and possible thresholds of change as well as on effects of policy and implementation of coping strategies***, by identifying key indicators of change in water quality of which several, including water temperature, can be modelled explicitly. Thresholds of dangerous change have yet to be identified. Besides maintaining standard measurements of streamflow in key baseline catchments, it is therefore recommended that more observations of water temperature be made in South Africa.

Recommendations for Further Research, Knowledge Dissemination and Technology Transfer

Owing to its wide ranging objectives and by virtue of its focus on methodologies, as well as being a demonstration of how projects in the future may integrate state-of-the-art climate change simulations with agro-hydrological models, several suggestions for future work present themselves:

- The evolving nature of the climate science and the projections based on the science suggests that the scenarios used to make an assessment should be periodically updated.
- The techniques used to downscale the climate projections are also continually evolving and improving. This also suggests that hydrological assessments should be reiterated when either Regional Climate Model data become available (e.g. through the CORDEX program) or when statistical downscaling techniques change or evolve.
- Regional feedbacks between climate, land use change, the ocean, fire and aerosols are all currently unknown and their effect on climate change projections should be quantified in the future.
- The ECHAM5 GCM was employed as the climate model in this research in order to project likely future climate conditions of key eco-hydrological indicators. The focus of this project was to *develop techniques / methodologies* to assess impacts on climate change on eco-hydrologically related indicators, and because of this focus, only one GCM was used. However, projecting into the future is always linked to uncertainties, especially with models as complex as those simulating future climate systems. In order to reduce this uncertainty and

assign levels of confidence to results, output from a series of GCMs should be used in order to obtain a probability distribution of, and a level of confidence on, the climate impacts being modelled.

- All *ACRU* model simulations in this research were performed using baseline land cover information, with the reference vegetation being Acocks' (1988) Veld Types. The incorporation of detailed actual land use information and of the water engineered system (e.g. dams, irrigation and return flows) would significantly enhance the usefulness from the hydrological modelling on catchments where crucial real-world decision may need to be made.
- In this research project only a subset of all the available flow indicators was applied with the three climate scenarios. In order to fully describe South African rivers' flow regimes from an ecological perspective, climate change responses from all 67 available indices should be modelled. Therefore, in future projects investigating the likely impacts of climate change on flow regimes it is recommended that methods and techniques be developed to assess all 67 indices.
- The equation used to estimate maximum water temperature was developed in the Sabie River Catchment, but has been shown to be acceptably robust for other regions in South Africa. However, regionally co-correlated equations could provide more regionally relevant results on modelled water temperatures. Furthermore, a more complex equation could be employed to estimate maximum water temperature, as the equation in its current form is fully reliant on the accuracy of the mean air temperature data only.
- The Thukela Catchment was used as the test catchment for the water temperature related analysis in this research project. The techniques developed to assess the impact of projected climate change on the water temperature parameters produced workable results and thus it is recommended that a study covering southern Africa be performed.

CHAPTER 1 DEVELOPING REGIONAL CLIMATE CHANGE PROJECTIONS

B.C. Hewitson and M.A. Tadross

1.1 Introduction

The development of regional climate projections is often viewed as an objective in itself, and the assumption is then made that if one can merely attain this, then all the regional climate-change questions can be solved. However, this assumes that regional climate changes are the only stressor (whereas one needs to account for a multi-stressor context), and that there is, in fact, a definitive regional future climate (as opposed to an envelope of possibilities), or that it is even possible to generate a useful regional projection (which relates to the issue of data versus information). This introductory chapter outlines the issues in this regard and presents the approach adopted here to achieve two forms of regional projections, viz. descriptive messages of the projected changes and quantitative data of the projected change for application in impact modelling.

It is important to recognise that the understanding of climate change is incomplete (but not uninformative) and is evolving, will continue to evolve, and that the associated information as presented here is necessarily a snapshot in the progressive development of our understanding, which will change. This is not to say that the developments will negate current understanding, rather that in recent decades the development has always reinforced the base understanding, but has then provided additional detail and nuances. All indicators are that this will continue into the future.

Using climate change projections is an activity fraught with potential problems, many related to inappropriate usage of the available data and its over-interpretation. For this reason the first part of this chapter focuses on principles and concepts central to right of usage of climate change information. **Figure 1.1** shows a conceptual framework for interpreting climate change information. One considers two axes: one moving from data through to knowledge, and one from awareness through to action. In most cases one begins in the lower left quadrant where one is aware with available data. Two inappropriate paths are available: the first is to translate data into knowledge, but yet take no action, and the second is to take action on the face value of the data without understanding its limitations. Both these paths carry a high risk of unwelcome outcomes. Ideally one would hope that the pathway leads to the upper right quadrant, where appropriate action is taken on the basis of the knowledge content of the data.

1.2 Conceptual Framing of Regional Climate Change Projections

Central to this discussion are three conceptual issues to be aware of, viz. first, what messages of regional change are possible, secondly, what the application value of the messages is, and thirdly to make the distinction between data, information, and knowledge.

1.2.1 Possible messages

With regard to the information one is seeking, the possible messages that one may be generating, and the current capacity to develop these are as follows:

- *Can one say something useful about regional climate change or not?* This might sound facetious, yet it is important to understand that for some regions the skill of the science is such that one is not yet able to provide an answer to some regional questions of future change. For

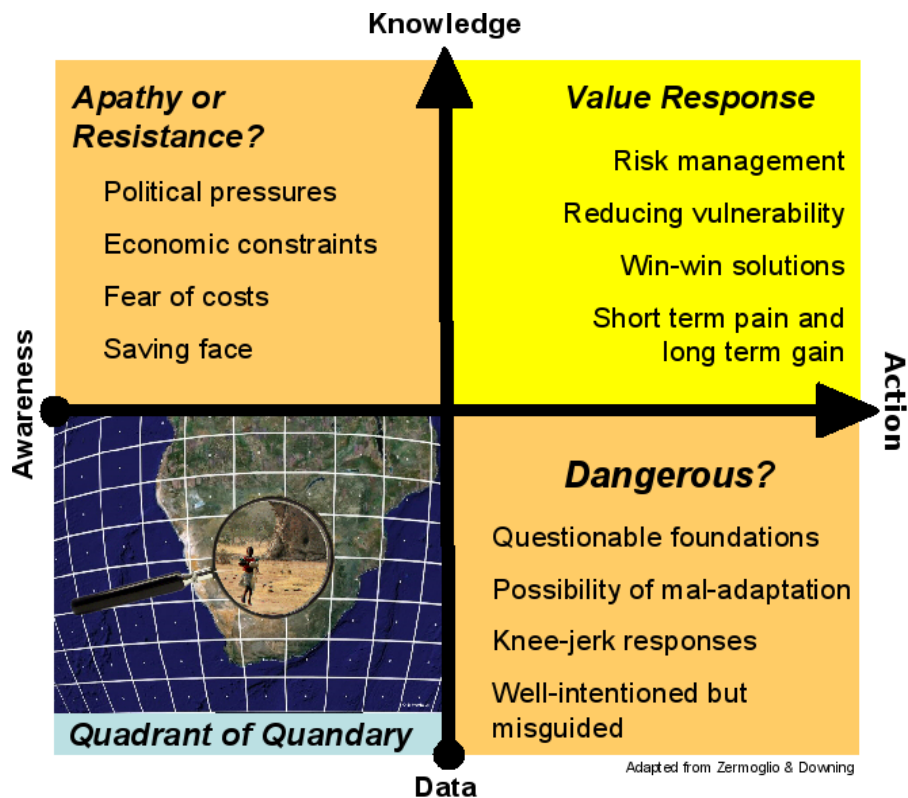


Figure 1.1 Conceptual framework for considering user pathways of response to regional climate change information

example, we do not yet have skill in making robust statements for the next decade, nor about how climate change will impact the low frequency but high impact extreme events such as the 1 in 100 year flood.

- *What will be the direction of change in the future?* In other words, will it get warmer or cooler, wetter or drier, more variable or not, etc. Currently the answers are conditional on time in the future, where one is focusing, and what attribute one is considering. Thus, for example, we are in a position to make robust statements about the direction of temperature changes by mid-21st century, somewhat robust statements about the sub-continental rainfall changes, and weaker statements about soil moisture conditions in the future in, say, the Limpopo province.
- *What will be the magnitude of change?* This is the most challenging element and it is a fundamental principle that for future climate change one must necessarily consider a range, or envelope, of possible futures because of the semi-stochastic nature of the climate system and the differential sensitivity of the modelling tools to anthropogenic forcing. Again, the answers are conditional on time in the future, where one is focusing, and what attribute one is considering.

There is not always the need to achieve answers at the level of the third point made; for a funding agency one might need only to recognise the answer to the first, while for policy one may need only have an understanding of the second. Yet for application to impacts modelling, as is undertaken in this project, one needs some measure of the third point made.

1.2.2 Application value of regional projections

It is relatively easy to generate a future climate projection with the many tools and approaches available to do so. At the same time it is quite easy to rationalise the projection as one that may be

believed. This, however, can lead to significant problems from unrecognised misuse of the information. Three levels of quality may be recognised as plausible, defensible, and actionable.

- *Plausible information* is that which appears to reflect reality, i.e. it is, recognisably showing the characteristics of the geographic region under consideration. This is the basic minimum before consideration of any value.
- *Defensible information* is that which can be explained in terms of physical climate processes, for example, a decrease in cold front intensity over the southwestern tip of South Africa as a function of an intensification of the Hadley circulation. The value of information here is that there is a basis for valid interpretation of the real world implications, at least in general terms of the direction of indicated change.
- *Actionable information* is information that is robust to the point that, in terms of risk management strategy, there is justification to implement a response action through adaptation and/or mitigation measures.

Naturally one wishes to achieve actionable information in all cases; but for the present much of the information remains at the defensible stage, with some cases only making an actionable category. For example, in the case of a temperature sensitive user sector in the north central region of South Africa who is currently close to the upper operating limit under the present climate, the information on future temperature changes would be considered actionable. In contrast, the information on extreme events in, say, Gauteng, is plausible and defensible, but has a relatively low confidence in terms of being actionable.

1.2.3 The disparity between data, information, and knowledge

Referring back to **Figure 1.1**, the starting point for assessing climate change is with the data. Too often, however, the data are perceived to be more accurate than they actually are, and over-interpretation or mis-interpretation becomes a very easy and all too frequent consequences are implied from such data. The fundamental premise that is often missing is that data are not information, but may contain information in the midst of noise, and that information is not knowledge which needs to be interpreted on the basis of information. Thus two steps are required to validly use the data.

First is the need to assess whether the data contain information, or to what degree the data are mere noise. For example, one can run a climate model and obtain data that looks plausible (cf. **Section 1.2.2**, third point). However, if the data are for a region strongly influenced by, for example, El Niño, yet the model does not capture the El Niño process adequately, then it is legitimate to question whether the data have any information more than a plausible reflection of the regional climate. Achieving an assessment of the information content is usually through processes of cross validation, for example, by comparing the data with known observations. This is, however, a non-trivial task, and is still a key research area of importance within the theme of addressing uncertainty. Nonetheless, some indications of information may be achieved.

Second is the need to interpret information into knowledge, i.e. to say that on the basis of this information one may understand the indicated messages. For regional climate change this is a process of considering all information available across as many data sources as possible, and is discussed in greater detail in the sections that follow.

1.3 Understanding and Interpreting Change Information

Conventionally, climate is conveyed in the first instance as mean values of temperature and rainfall. However, in terms of societal impacts and relevance to different sectors and natural systems, there is a range of concepts that are central to correct interpretation of data and information, most especially as regards global change and anthropogenic aspects. This section briefly introduces each of these and discusses their relevance to a more correct understanding of climate change issues.

1.3.1 Detection versus attribution

One of the first natural questions posed when talking about climate change is, “what has changed?” Often the inference is automatically, but incorrectly, made that identified changes are attributable to anthropogenic climate change. Detection of change is a comparatively simple task, as shown in **Section 3**. Attribution, i.e. the distinction that one can ascribe the cause of the detected change, is considerably more difficult. Detection of the change in global mean temperature has long been established, whereas defensible attribution of much (but not all) of this change to human factors is only a recent development (cf. IPCC AR4, 2007), and then only at the global scale.

Detection of regional change is, likewise, comparatively easily. Attribution of identified regional change is, however, yet to be robustly demonstrated. While plausible, and even persuasive arguments as to how anthropogenic change may be causing a detected regional change, the attribution step to say that human activities and not natural variability caused the regional change is much more difficult. Typically such work involves modelling the climate system with and without greenhouse gas forcing to assess the degree to which regional change is attributable to human factors.

At present such an analysis has yet to be completed for southern Africa, although work is in progress within the *climateprediction.net*¹ framework.

1.3.2 Prediction versus projection

Weather forecasts are a product familiar to most of society, and they represent a prediction. That is, a prediction seeks to state what *will* occur as a required outcome that evolves from the current state of the system. Most people readily recognise that a prediction may sometimes (often-times?) be wrong, but nonetheless accept it as a statement of the best understanding of how the system will develop in time.

By comparison, the information on future climate changes are is not a prediction. It is not a statement of what the future will necessarily be, but one that, given the expected (but changeable) development of key factors will be a *probable* outcome. Thus, one seeks to make a projection of possible futures – scenarios of varying likelihood subject to some unknowns. There are a number of aspects that introduce uncertainty into this projection, not least of which are question of future greenhouse gas emissions. This distinction between prediction and projection may seem unnecessarily subtle, but it is absolutely critical to the right handling and appropriate application of information about future climates. Even the IPCC does not make predictions, but explores possible scenarios that are consistent with the growth of greenhouse gas emissions.

¹ See <http://www.climateprediction.net>

1.3.3 Principles of robust messages

Developing a robust understanding of regional change on the time and space scales of relevance requires the integration of information from number of sources, viz.

- past trend; what has changed, recognising that this is not a guarantee of continued future change,
- changes in relevant driving processes on synoptic to global scales; assessing the physical basis of the climate system that drives the regional change,
- model projections of change; exploring the dynamical response of the earth to the imposed anthropogenic forcing against a background of natural variability,
- regional expressions of future global change; these are usually derived through dynamical and/or statistical downscaling, and
- an assessment of uncertainty; all information is limited by a wide range of uncertainty sources that do not preclude deriving value information, but which does cloud the issue to differing degrees.

By drawing on the understanding of these complementary aspects it is possible to develop a more robust understanding of the climate system variability and change on regional scales. Ignoring one or other source of information leads to a risk that key elements of the information will be missed. Moreover, the research on each of these aspects is not equally mature, and is continually evolving. Thus it requires responsible recognition that numbers (data) are not information, that information is not knowledge, and that deriving robust messages requires critical assessment in the context of the intended application.

1.3.4 Envelopes and thresholds

There is one history, but many possible futures. Therefore, in mapping future projections one seeks to explore the envelope of possibility. As such, projections of future climate implicitly must take cognisance of the range of projections subject to factors such as alternate emission scenarios, different model responses, and that all projections are likely but a subset of the true envelope of possibilities.

Secondly, the interpretation of climate information relevance is necessarily tied to thresholds. A shift in mean climate is largely of minimal value in terms of impacts, vulnerability, and adaptation. Systems (biophysical or societal) operate within limits, and it is through exceeding these thresholds that the impact of change is most commonly found. However, thresholds are specific to the sector under analysis. For example, biome stability, ecosystem viability, or water resource infrastructure all have their own thresholds of tolerance, making it difficult to generalise the messages from regional climate change impacts.

There are four levels of value in climate change messages, each progressively more difficult to attain:

- Whether or not there is a possibility to generate useful information for a given location / variable (it is not always possible to generate a useful message on regional change),
- The likely direction of change (positive or negative, or equally importantly, no change),
- The attributes of indicated change (changes in the mean, the extremes, derivative parameters, etc.), and
- The absolute magnitudes of change, or at least the probable range.

1.3.5 Uncertainty

The question of uncertainty is arguably the single largest issue currently faced when dealing with climate change. Importantly, uncertainty does not mean that there is not information, but merely that the information is not definitive, and that there is room for question or reserve judgment on some aspects of the information. There are many possible sources of uncertainty, including issues of emission scenarios, the choice of climate models, quality of historical data, methods of downscaling global data, etc. An often ignored attribute of uncertainty, yet one particularly relevant to South Africa, is what may be termed “boundary uncertainty”. This refers to the situation where a geographic region of concern lies on the boundary of two regions showing strong, but opposite, direction of change. In this case the change in the region is highly sensitive to the spatial position of the boundary. This is especially relevant to the interior of South Africa where future projections generally show the west coast drying and the east coast wetting, and the positioning of the boundary within the country’s interior is not clear.

1.4 Future Projections

Projections of the future climate are, as already discussed, not a prediction, but an assessment of the plausible and likely futures. The skill of projections is strongly dependent on how far in the future one looks, the temporal and spatial scales in question, which variables, which models, which greenhouse gas emissions pathways are considered, etc. As discussed in **Section 2**, deriving the key regional messages requires assessing multiple information sources.

At its root all regional change is driven by changes in the circulation of the atmosphere, coupled as it is to the complex inter-linkages of regional and global forcing and feedbacks. Substantial and valuable information can be drawn from understanding how such large scale processes are projected to change. These large scale attributes are the primary strength of GCMs which are most skilful with respect to circulation and large area averages of surface variables. Notably, GCMs are least skilful at their native (coarse) grid cell resolution - typically around 250 km by 250 km for a single grid cell - and especially so for grid cell rainfall. Thus, while map representations of GCM projections suggest detailed regional information, such maps encourage a fine spatial interpretation which is not defensibly valid. For example, the maps in the IPCC AR4 show detailed smooth maps for southern Africa, and while the broad scale features may be somewhat robust, they are not valid for sub-national and local scale interpretation.

It is very important that climate projections be assessed from as many models as possible; one model alone is a dangerous basis for developing regional change messages, and each model brings additional information value. Thus the regional projections need to be assessed in terms of the envelope and spread of the indicated changes across the available models. While it is tempting to select one “best” model, there is no best model across all relevant measures. Likewise one may seek to weight the models relative to each other according to some measure, but such weighting remains a challenging task. One approach to weighting is to assess the skill of a GCM in simulating the 20th century. However, even then such skill does not imply it is necessarily skilful at capturing the projected **change** factor for the future. Likewise, agreement between models on the sign of the projected change (an approach such as is used in the IPCC AR4, Ch 11) also does not necessarily indicate that agreement is actual agreement on the right, for a range of technical reasons. Consequently, within the current state of the science, it remains important to assess the spread of the results across models. The GCM data used here are drawn from the CMIP3 archive of GCM simulations which were assessed in the IPCC AR4.

The World Climate Modelling Summit in 2008 noted that to use GCMs directly for regional studies “... means making their simulations good enough to guide hard decisions, ... the adaptations required to meet changing rainfall and extreme weather events on regional and local scales. **Today’s modelling efforts, though, are not up to that job.**” (Editorial in Nature, 15 March 2008).

Thus, to complement GCMs, the large scale changes are typically *downscaled* - whereby the large scale from the GCMs is translated to the local user-relevant scales. Downscaling is accomplished through statistical downscaling, Regional Climate Models (RCMs), or high resolution and variable resolution global models. All three approaches use the GCM’s large scale forcing, and are thus dependent on the GCMs. Downscaling is, in effect, a scale translation technique to add spatial detail consistent with the large scale changes in the GCMs. The different downscaling approaches have relative merits and shortcomings, but are, in principle, considered to be of comparable skill (cf. Chapter 11, IPCC AR4). The IPCC DDC has a comprehensive guidance paper on the relative attributes of the two techniques.

At present the dynamical downscaling approaches has not been implemented over southern Africa to the extent that there is a robust spread of multi-model information. This is likely to change in the near future as the CORDEX experiment begins to produce results. Thus the bulk of the regional and local scale projections that include appropriate representation of the envelope of future climate from multiple GCMs are based on statistical downscaling. This approach uses 9 GCMs which are downscaled to a 25 km grid resolution over South Africa. Owing to constraints in the available GCM data from the CMIP3 archive, it is only possible to downscale the last 30 years of the 20th century and two periods of twenty years each for the 21st century, viz. 2046-2065 and 2081-2100. Downscaling is especially important for South Africa as the GCMs fail to adequately capture the detailed spatial gradients and strong topographical forcing that is so important to South Africa’s climate.

Sections 1.4.2 and 1.4.5 use the available sources of information as described above, and integrate these into key messages that may legitimately be interpreted from the data.

1.4.1 Role of emission scenarios

The GCM simulations are forced by emission scenarios that describe the possible anthropogenic changes in future greenhouse gas concentrations. The model simulations data in the CMIP3 GCM archive is based on a range of emission scenarios from the SRES set, but the differences in results up to 2050 are small, with the impact of the emission scenario only fully apparent in the latter half of the 21st century. Currently two emission scenarios are the principle focus, viz. the SRES A2 and B2 scenarios. For South Africa the downscaled applications have focused on A2, a moderately high emission scenario characterised by a heterogeneous world with increasing global population and regionally oriented economic growth. The focus in this chapter is on the changes by the middle of the 21st century as this is the most relevant time frame where the choice of emissions scenario has limited impact.

1.4.2 GCM projections: Regional circulation changes

Figures 1.2 to 1.5 show three aspects of the projected change in regional circulation, respectively the sea level pressure, wind velocity, and wind direction. In each case the anomalies are shown, i.e. the difference between the projected future and the present. From the spread of GCMs the lower 25th percentile, the median, and the upper 75th percentile are calculated to indicate the primary spread of the indicated change from the different models. In addition the figures show the changes by quarter-year season (where DJF is the summer quarter December to February, MAM is the autumn quarter

March to May, JJA is the winter quarter June to August and SON is the spring quarter September to November), and the projected change by the mid-21st century (2046-2065; the intermediate future) and by the end of the 21st century (2081-2100; the more distant future).

The primary large scale circulation changes indicated are:

- An increase in the intensity of the continental surface low pressure trough associated with an increased surface warming,
- An extension of the Hadley circulation expressed as an increased surface pressure poleward of the continent, and increases in the southern margin of the oceanic high pressure systems associated with the Hadley cell expansion,
- A regional strengthening of wind velocity, primarily along the west coast and in summer,
- A decrease in the strength of the prevailing westerly winds south of the continent, and
- A moderate increase in air flow transport onto the continent from the east, this being of key relevance in that it enhances the moisture transport into the region of air that is also becoming more moisture laden as the world warms.

These circulation changes suggest a number of consequences for the regional climate response, which include:

- Likely strengthening of upper air subsidence over the continent, with implication for stronger elevated inversions that can inhibit weak convection.
- Shifts in the spatial west-east positioning of the summer rainfall gradient.
- Stronger long-shore winds on the west coast with implications for coastal upwelling.
- Increased moisture content over the continent (in regard to absolute, not relative humidity), which would translate to potentially more intense precipitation when it rained, as well as a likely increase in orographic cloud cover and topographically induced rainfall.
- Weaker frontal systems to the south, which would translate to weaker penetration of fronts onto the continent, drier conditions in the Western Cape (possibly compensated for in the mountains by an increased orographic rainfall), and an as yet indeterminate impact on the occurrence of tropical temperate troughs.

Across the range from the 25th to 75th percentile of the model range the message interpretation is not substantively altered, and the differences are mostly in terms of intensity. Likewise, the projections for the end of the 21st century are effectively a further intensification of the mid-century changes. These results reflect a robust first order response of the regional circulation to the global scale changes.

1.4.3 GCM projections: Surface variables

The surface variables from the GCMs (**Figures 1.2 and 1.3**) are shown as anomalies, as was done for the circulation variables in **Section 1.4.2**. Care should be taken that one does not interpret these figures at a single grid cell as the model values are not robust at that scale²; rather one should focus on the pattern of change. Most importantly it is critical to understand that the models poorly represent the escarpment and coastal mountains, and hence key surface responses that are strongly modulated by the topography are likely to be inadequately represented in the GCM grid cell values for these regions. Chief among the variables of concern in this regard is precipitation, which should be viewed with special caution at single grid cells on the native GCM grid.

² For this reason the maps are plotted with actual grid cell sizes shown. The models vary in grid resolution but are all nominally similar, and the data here have been interpolated to a common indicative grid of 2° latitude by 2° longitude.

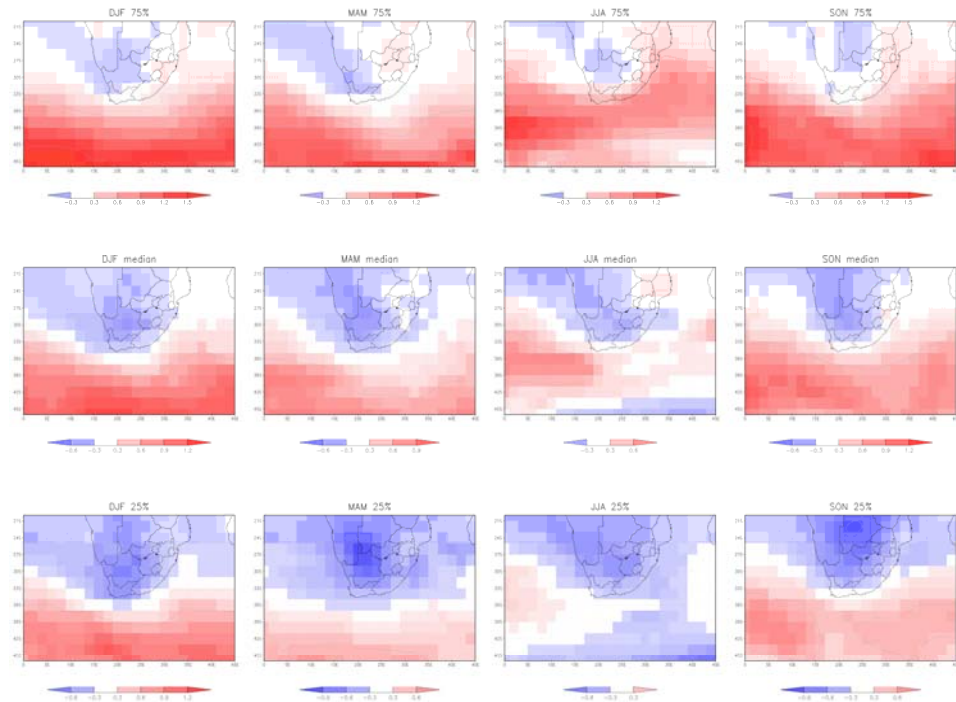


Figure 1.2 Sea level pressure anomalies for the intermediate future (2046-2065)

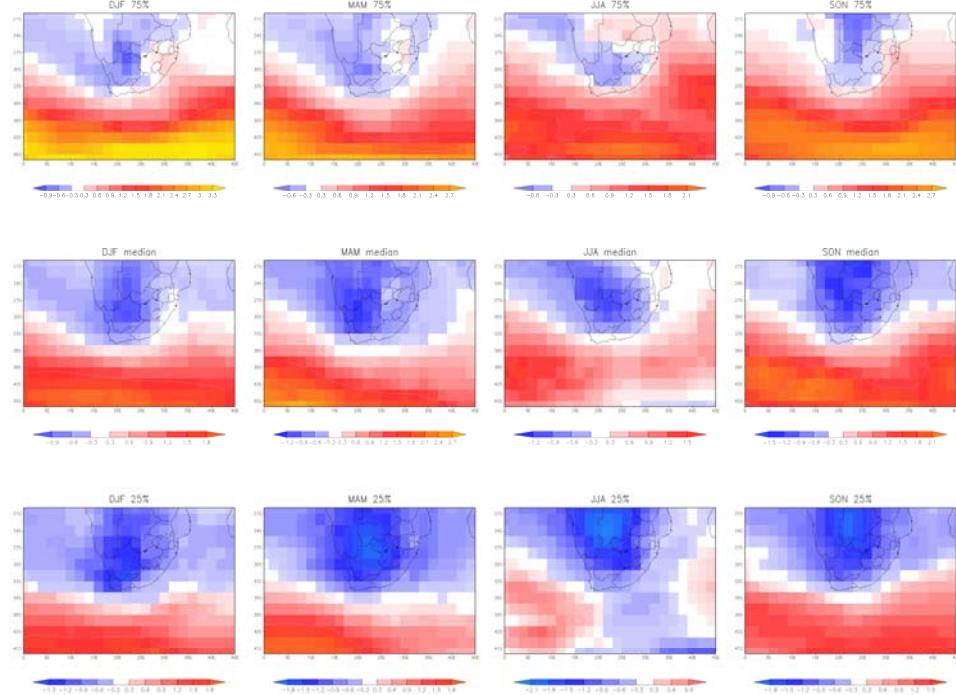


Figure 1.3 Sea level pressure anomalies for the more distant future (2081-2100)

When viewed in terms of the sub-continental pattern response, the results are physically consistent with the indicated large scale process changes described in the previous section, and this increases the confidence in the pattern of indicated change. The magnitude change across the range from 25th to 75th percentile is, however, quite large, to the point that in some regions the sign of the change can be reversed. Nonetheless the relative *pattern* remains largely stable.

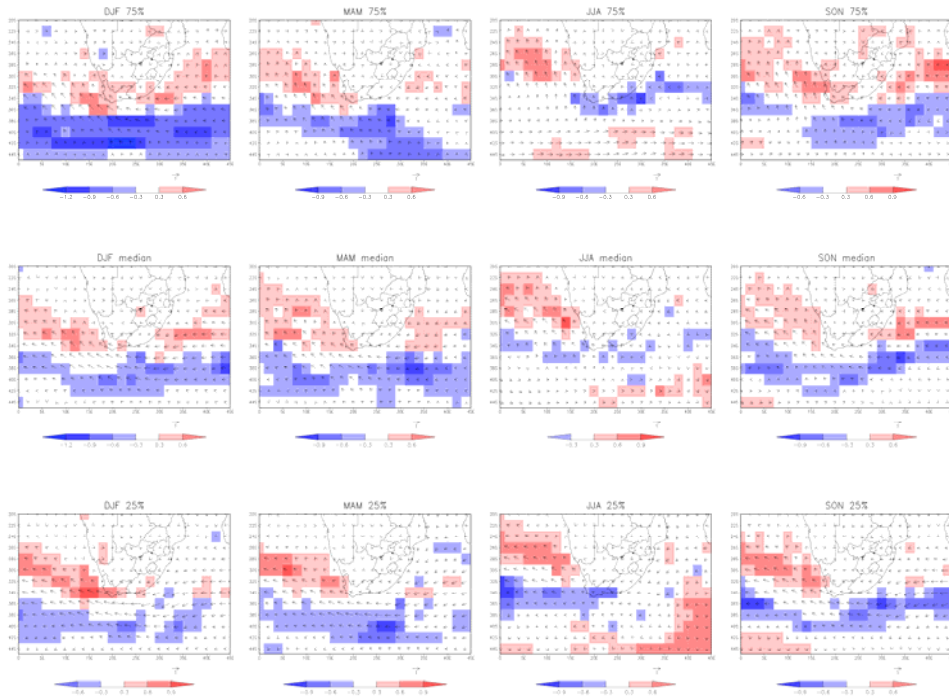


Figure 1.4 Wind velocity and direction anomalies for the intermediate future (2046-2065)

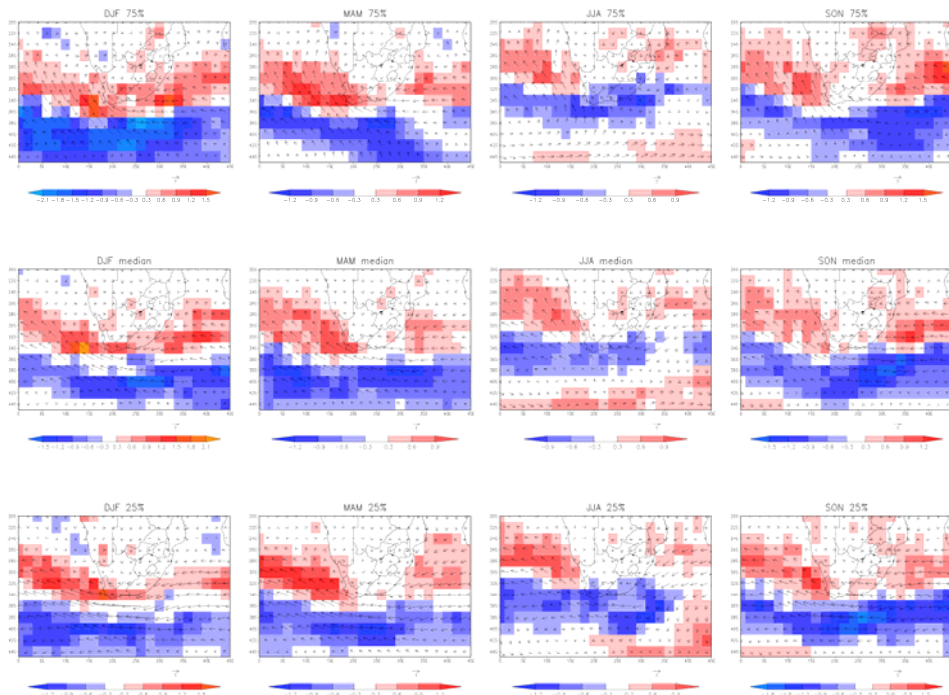


Figure 1.5 Wind velocity and direction anomalies for the more distant future (2081-2100)

For precipitation (**Figures 1.6 and 1.7**), the changes indicate drying to the northwest, contrasted in the east of the country with increased summer rainfall (or smaller decreases). Winter rainfall over the southwest is shown to decrease. Beyond this it is difficult to substantiate any stronger messages about precipitation when based only from the GCM grid cell data. Most problematic is the difficulty in determining the position of the boundary between wetter and drier regions which, from these data, is a key uncertainty.

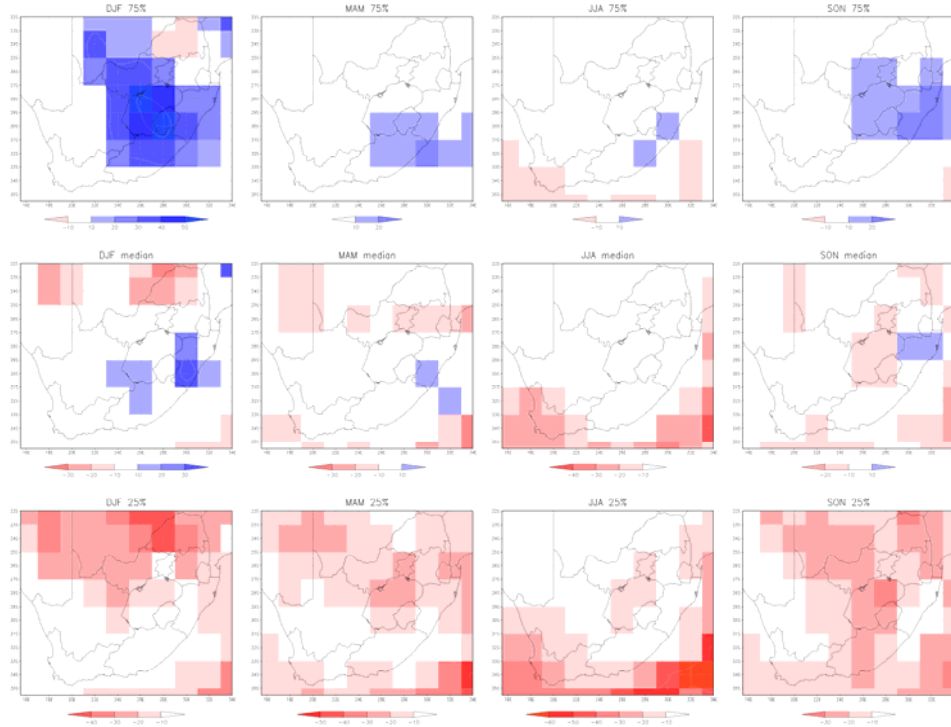


Figure 1.6 Total seasonal precipitation anomalies for the intermediate future (2046-2065)

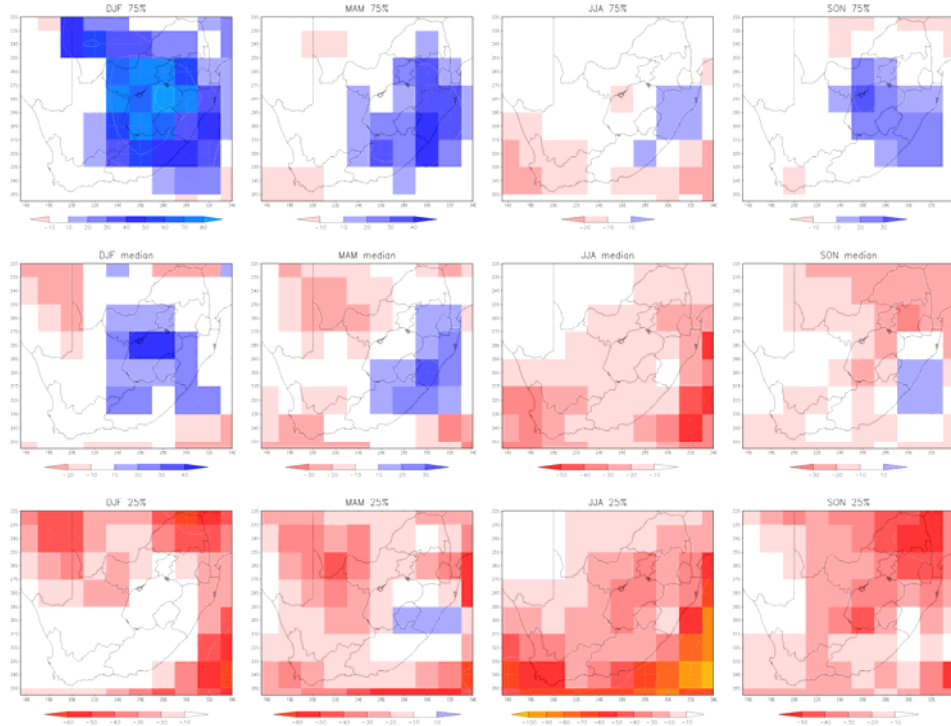


Figure 1.7 Total seasonal precipitation anomalies for the more distant future (2081-2100)

Surface air temperature (**Figures 1.8 and 1.9**), a more spatially continuous parameter, shows a general change of warming everywhere, but most strongly in the interior. Coastal warming is of the order of 1°C increasing to around 3°C in the northern interior by the middle of the 21st century. By the end of the 21st century the warming is greater still, but at that time scale the degree of warming will be strongly dependent on the scenario of future greenhouse gas emissions.

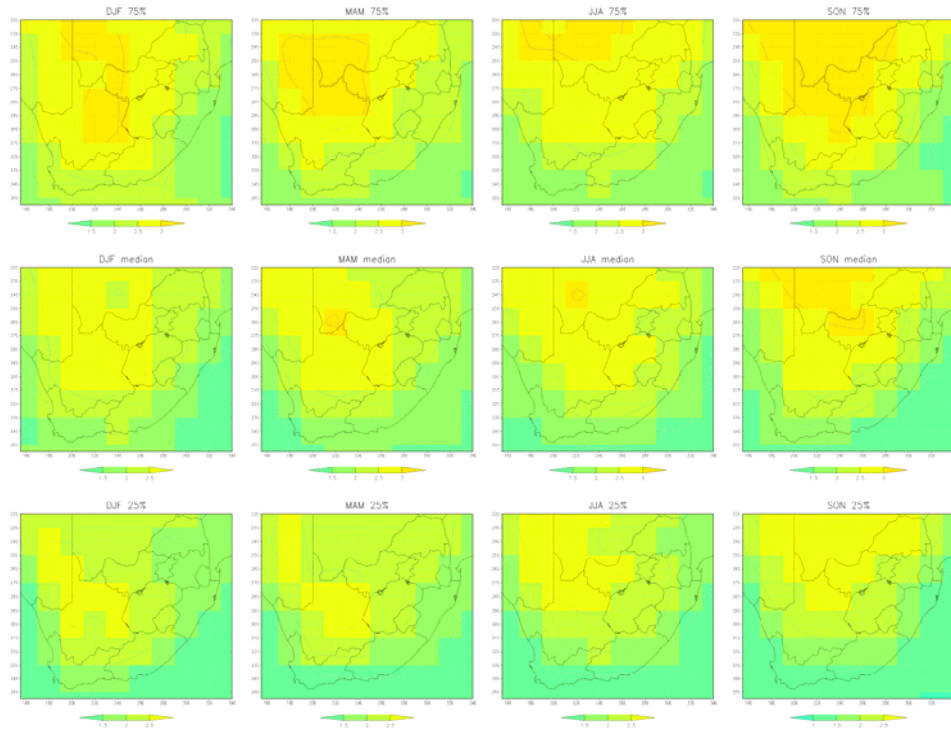


Figure 1.8 Average surface temperature anomalies for the intermediate future (2046-2065)

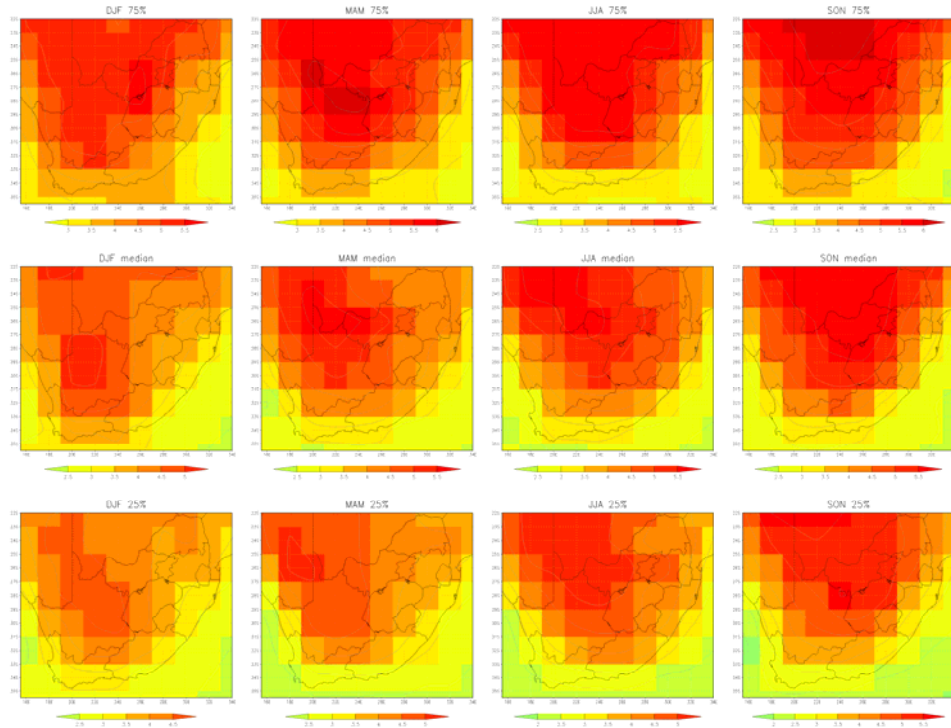


Figure 1.9 Average surface temperature anomalies for the more distant future (2081-2100)

Jointly the raw GCM rainfall and temperature changes suggest a potential for decreased soil moisture as a result of the increased temperatures and the drying tendency for much of the region. However, these should be viewed in light of the downscaled data (following section) as well as the large scale circulation change; as discussed later in **Section 1.4.5**.

1.4.4 GCM downscaled projections

The downscaled data are generated as daily time series for precipitation, minimum and maximum temperature. From these a suite of derivative attributes are also derived, including dry spell duration, rain day frequency, extreme values, frost day frequency, etc.

Since the downscaled data are derived from the GCM atmospheric fields, validation of the downscaling is warranted. Assessment of downscaling is usually accomplished by applying the downscaling to historical atmospheric circulation and comparing the results with actual observed high resolution observations. **Figure 1.10** shows one such validation. In this case an assessment of the downscaling from the NCEP reanalysis atmospheric data which has a latitude-longitude grid resolution of 2.5° (comparable to climate simulation data from GCMs), and compared against the gridded observed precipitation for the same period (cf. Hewitson and Crane, 2006). The figure shows that the observed accumulated precipitation for the two 6-month periods centred on summer and winter, the same as downscaled from the NCEP reanalysis atmospheric data. As can be seen, the results are markedly similar indicating the robustness of the technique in downscaling from atmospheric fields.

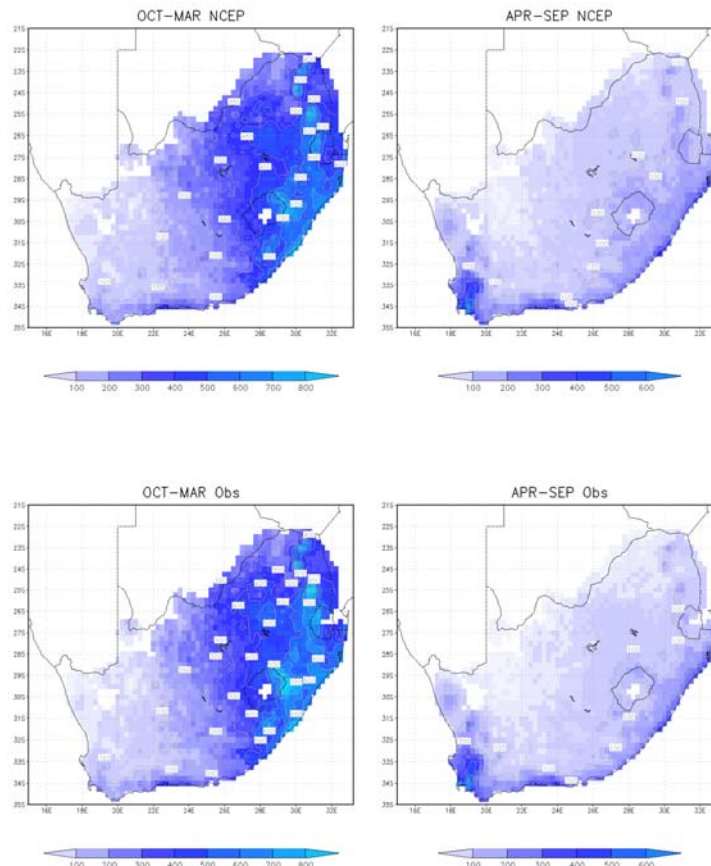


Figure 1.10 Downscaled accumulated precipitation from the NCEP reanalysis atmospheric data (top row) and from observations (bottom row) for the two 6-month periods centred on summer and winter

Figures 1.11 and **1.12** show the precipitation change downscaled from the GCM climate change simulations in the same form as was done for the GCMs raw grid cell data (**Figure 1.6**). In this case the downscaling represents the precipitation response at a high spatial resolution (0.25°) that is dynamically consistent with the large scale circulation and atmosphere state of the GCMs. The

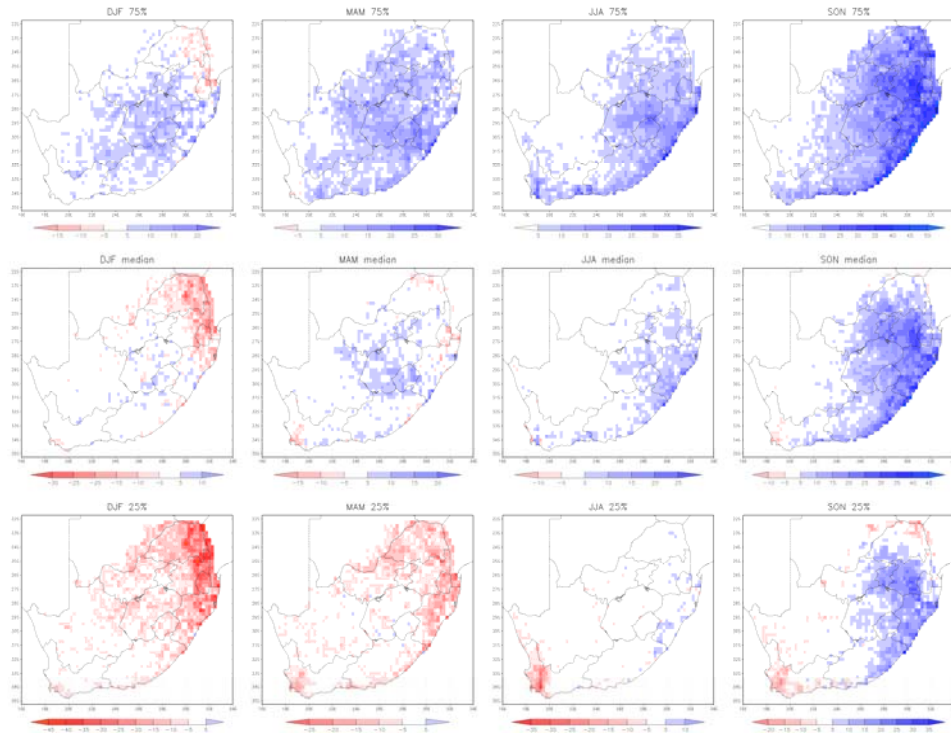


Figure 1.11 Downscaled seasonal accumulated precipitation anomalies for the intermediate future (2046-2065)

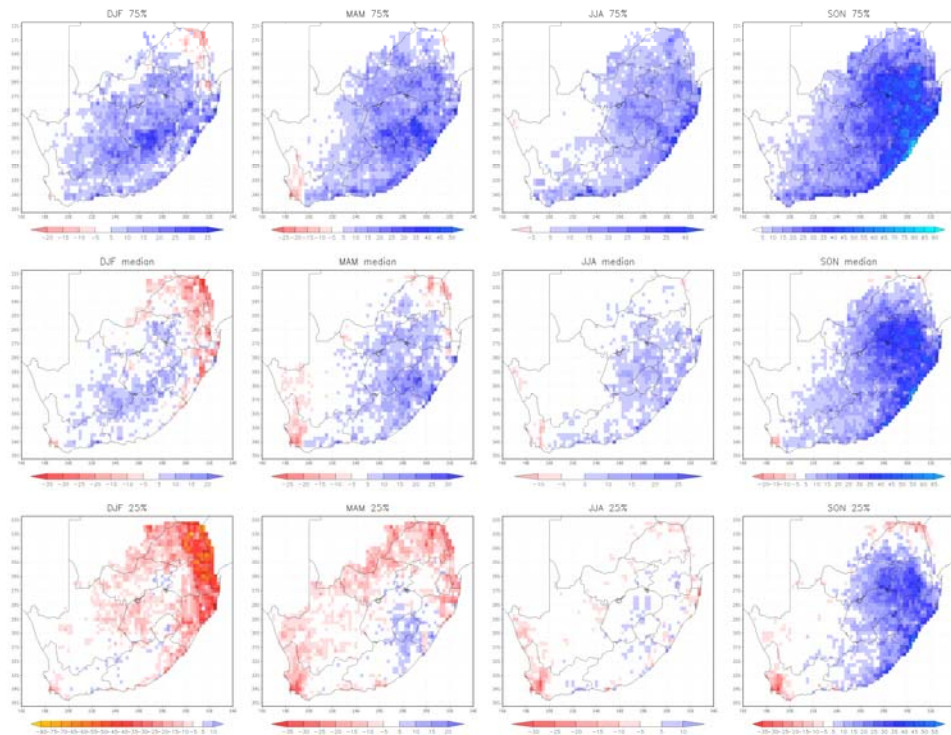


Figure 1.12 Downscaled seasonal accumulated precipitation anomalies for the more distant future (2081-2100)

The derivative attributes of the downscaled rainfall, viz. intensity, dry-spell duration and rainyday frequency, all support these findings.

1.5 Drawing Conclusions

By linking the GCM grid cell response, downscaling results, and the indications of large scale circulation change, and considering the relevant strengths and weaknesses of each data form, some consistent messages can be identified.

- Climate change for South Africa, both past and future, cannot be reduced to simple national scale messages without obscuring important sub-regional differences. At the regional and local scale there can be substantial complexity that requires a rational assessment of multiple sources of information in order to arrive at a robust message of change.
- For some climate variables, and for some regions of the country, it is not yet possible to formulate a clear message regarding future change. This is largely so because when a region is on the boundary between locations having signs of opposite change, it is highly sensitive to the uncertainty in the spatial positioning of the boundary.
- Temperatures across the country have increased in the historical past, and are projected to increase into the future throughout the 21st century. The warming will be greatest in the interior of the country and less along the coast. Assuming a moderate to high growth in greenhouse gas concentrations (SRES A2 scenario), by mid-century the coast is likely to warm by around 1°C and the interior around 3°C. By 2100 under the same scenario the warming is likely to be around 3°C on the coast and 5°C in the northern interior.
- Future rainfall changes are regionally complex, especially in areas of strong topographical forcing. In general there are indications for a wetter east coast in summer and a drier west coast, with drier conditions in the southwest of the country in both seasons. The west-east pattern of precipitation response seems stable across the range of models, and is physically consistent with the circulation changes, yet has with notable uncertainty in the magnitude of the response. The role of topography is critically important, especially as pertains to potentially enhancing increase in precipitation on the east coast. Beyond this the messages are more complex, and hinge on the interaction of the increased atmospheric moisture content with topography and changing convection. The key uncertainty of concern is the difficulty in robustly identifying the west-east spatial position of the boundary to the east coast wetting.
- There are indications that rainfall intensity is likely to increase. This does not necessarily equate to an increase in total rainfall, but that when it does rain, the intensity is likely to be greater.
- Evaporation is likely to increase as a result of higher temperatures. This is likely to increase the incidence of drought potential (as defined by the response of available soil moisture and available free water), possibly even if the total rainfall of a region increases.
- The continental high pressure system is likely to intensify resulting in enhanced subsidence and consequent persistence of the inversion in the interior.
- Coastal winds are expected to intensify on average into the future, while the mid-latitude westerlies (important for cold fronts) are projected to decrease in strength.

CHAPTER 2 CLIMATE CHANGE AND AQUATIC ECOSYSTEMS

K.R. Barichievsky and R.E. Schulze

2.1 Introduction

Aquatic ecosystems consist of living organisms as well as the physical non-living (abiotic) environment, i.e. the rocks, soils and water (Cotgrave and Forseth, 2002; Clausen *et al.*, 2004). Aquatic ecosystems range from open oceans to freshwater lakes, streams and rivers (Giller and Malmqvist, 1998). In this chapter the focus is on running freshwater, or 'lotic', systems and the term "aquatic ecosystem" will be used in specific reference to these flowing freshwater habitats. The roles and benefits provided by aquatic ecosystems are investigated, followed by a discourse on how the system's flow regime plays a critical role in maintaining a healthy aquatic ecosystem. Finally the potential impacts of climate change on aquatic ecosystems are discussed.

Flowing water systems come in many shapes and sizes and comprise a large array of intergrading types of water channels, including streams, drains, tributaries and/or floodplain rivers (Downes *et al.*, 2002). Water is the primary driving force within this habitat and determines the soil, vegetation and organism characteristics found within aquatic ecosystems. Both the vegetation and soil found in aquatic ecosystems play critical roles in determining adequate hydrological functioning and it is the integrated relationships between vegetation, soil and water that determine many hydrological attributes found within freshwater ecosystems. These attributes include the flow velocity of the water, as well as the frequency, duration, magnitude, timing and rates of change of flows. Aquatic ecosystems provide many goods and services which benefit both humans and the environment, and this role needs to be investigated in order to understand the importance of these systems.

2.2 The Roles and Benefits of Aquatic Ecosystems

Although aquatic ecosystems and other similar wildlife habitats have long been valued for their aesthetic values, they are also critical components of the global environment and essential contributors to biodiversity and ecological productivity (Poff *et al.*, 2002). More than this, aquatic ecosystems also have both a socio-economic importance and humans have come to realise that aquatic ecosystems are a large source of natural products that they can utilise. The rise in awareness of the importance of aquatic ecosystems has much to do with an enhanced appreciation of their many positive, ecological and environmental functions and values (Williams, 1991). In South Africa, and around the world, human induced pressures on freshwater ecosystems have increased with the ever-increasing human population and associated agricultural and industrial development.

Aquatic ecosystems benefit humans in various ways and the most important of these is as a water resource. A river, or water impoundment, lies at the heart of all aquatic ecosystems. River water is seen as a usable renewable resource, which can be utilised for drinking, food production and recreation (Boon, 1992; Poff *et al.*, 2002). Another benefit provided by rivers is the fact is that flowing water is able to remove and dilute waste and can also be used as a transportation medium of solutes and sediments.

Rivers form part of complex systems and generally represent an extremely important resource that humans can utilise. It is therefore not surprising that it has been recognised that humans have used rivers more than any other type of ecosystem (Boon, 1992). Rivers are important sources of nutrition

as there are many species of fish, amphibians, crustaceans and molluscs that inhabit these rich ecosystems. Hunting of game animals like antelope and water birds also occurs in order to supplement the diets of the people living in close proximity to the aquatic ecosystem. Building materials such as wood and thatch grass can often be found in abundance near rivers and the extraction of these natural products is yet another benefit of aquatic ecosystems to humans.

A detailed list of services from freshwater ecosystems includes many items that are undervalued in economic terms and often are unrecognised and unappreciated (IPCC, 2001). Although aquatic environments cover only a very small portion of the Earth, they play a vital role in many environmental cycles and related processes. For example, inland waters play a major role in biogeochemical cycling of elements and compounds such as carbon, sulphur, nitrogen, phosphorous and toxic substances (Stumm and Morgan, 1996, cited in IPCC, 2001).

Other than the benefits provided via physical functioning, rivers also provide the habitat for living organisms, whether they are plants, invertebrates, fish or mammals. Many species are adapted to the aquatic environment and cannot move into another habitat, which leads to a high level of endemism. Plants have adapted to this wet environment by being able to float, having long oxygen transporting tubes or having pneumatophores, which are above-ground root structures. All these adaptations allow a greater chance of plant survival in saturated habitats. The riparian zone is the source of extremely important structural components, such as aquatic debris, which are its main source of nutritional substrate for aquatic biota (Franklin, 1992). The success of aquatic organisms is a function of a number of interrelated factors which are driven by hydrological conditions which, in turn, are determined largely by the overriding climate regime.

There are many factors which affect the health, composition and diversity of biotas.

- *Foods (i.e. nutrients)* play an important role in determining the population size and diversity of biota in a given aquatic ecosystem. Essentially, the more food that is available, the greater the biomass a given ecosystem can sustain.
- *Channel substrate* (includes both sediment and organic matter) is important in the running water environment, as most organisms are closely connected to sediment availability. Channel substrate provides raw materials that create habitat structure, refugia and breeding grounds for aquatic organisms. Furthermore, channel substrate supplies and stores nutrients that sustain aquatic plants and animals (Baron *et al.*, 2003).
- *The water depth and streambed width* of a river define the physical space of an aquatic ecosystem, and thus can limit numbers of individuals the system can support.
- The *velocity* of the water current is important for transport of resources to organisms. These resources can be in the form of both dissolved nutrients and food. The current can also be a potential hazard and a limiting factor for riverine organisms. Water velocity has both a higher and lower threshold, which affects both biota population and diversity.
- *Water temperature* plays a major role in all processes in an aquatic environment (Coulson and Joyce, 2005). Temperature and light characteristics regulate metabolic processes, activity levels and growth rates, as well as distributions of aquatic organisms (Baron *et al.*, 2003; Clausen *et al.*, 2004).
- *Suitable water quality* is vital for aquatic ecosystems and is influenced by nutrients, water velocity and temperature. Dissolved oxygen and pH levels are often used to indicate water quality (Clausen *et al.*, 2004).

These six factors are determined from the flow regime of the given river system. These factors influence environmental variables within a river and thus influence aquatic communities within these

systems, forming a continuous gradient of conditions down a river's longitudinal axis (Rivers-Moore, 2003). This is the essence of the *River Continuum Concept* (Vannote and Sweeney, 1980), according to which biological communities form a spatial and temporal continuum, and species dynamics are in equilibrium with the dynamic physical conditions of the river channel. Thus biotic communities are predictably structured along a river's profile because of the relative uniformity of the abiotic conditions (Vannote and Sweeney, 1980).

Therefore, it can be concluded that the concept of a river's flow regime must be investigated in order to understand the complex nature of aquatic ecosystems.

2.3 Flow Regimes

Freshwater ecosystems require certain elements to continue providing the valuable goods and services described in **Section 2.2** above. One of the most important elements that maintains a healthy aquatic ecosystem is its flow regime. Hydrological regimes influence all ecosystem components as well as the evolutionary adaptations of organisms inhabiting the ecosystem (Naiman *et al.*, 1992). A flow regime consists of five components, viz.

- magnitude,
- frequency,
- duration,
- timing, and
- rate of change (Poff *et al.*, 1997; **Figure 2.1**).

The flow regime of a freshwater ecosystem is critical for regulating biological productivity and biological diversity, particularly in lotic systems. These aspects include baseflow, annual or more frequent intra-annual floods, rare and more extreme inter-annual flood events, the seasonality of flows and inter-annual flow variability (Baron *et al.*, 2003). Furthermore, hydrological patterns of ecologically healthy catchments are strongly related to the timing and quantity of flows, characteristics of seasonal water storage, the source area of streamflows and the dynamics of surface and subsurface flow exchanges (Naiman *et al.*, 1992). Natural hydrological regimes vary from catchment to catchment and thus water quality, the physical habitat and biotic interactions also differ from river to river, often showing regional patterns which result from similar influencing factors such as climate and topography.

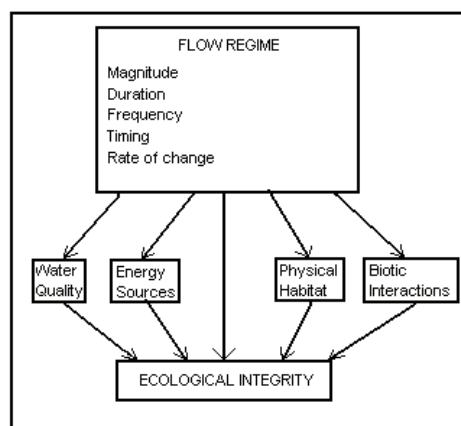


Figure 2.1 The effects of flow regimes on components which influence ecological integrity (after Karr, 1991)

Through the construction of and abstraction of water from dams, irrigation abstractions, urban and irrigation return flows, inter-catchment transfers and other abstractions which may be unsuitable/disruptive for the aquatic habitats, humans have altered the natural flow regime in many rivers systems and have thus compromised the ecological integrity of these aquatic ecosystems. The construction of large water impoundments has probably had the greatest impact on river flow regimes and many of the world's and South Africa's rivers have effectively become anthropogenically-controlled water engineered systems. Anthropogenically driven land use change is also a major driver of flow regime alteration. Land use change such as deforestation, poor land management, overgrazing, urban expansion and uncontrolled burning regimes have all played a role in altering natural flow regimes.

In South Africa the concept of instream flow requirements has been introduced in order protect aquatic ecosystems. This concept tries to mimic a river's natural flow regime, albeit at reduced volumes if there is an upstream impoundment, using controlled releases from dams and thus attempting to maintain some element of ecological integrity. Many years of streamflow measurement are required to describe the characteristic patterns of a river's flow such as its flow quantity, timing and variability (Poff *et al.*, 1997).

A river's natural flow regime is complex and contains both intra- and inter-annual flows. Intra-annual flows occur within a single year and show seasonal variation, i.e. periods of low and high flows. Many fundamental ecological processes are influenced by temporal flow variations which affect

- availability and persistence of habitats,
- species' access to habitats required for specific life stages, and
- fluxes of nutrients, materials and organic matter.

Temporal variations in streamflow occur naturally within a catchment in response to seasonal and inter-annual climate variation. For example, some species require high flows at specific times of the year in order to reproduce and so in the absence of high flows they do not sustain their populations (Meyer *et al.*, 1999).

A river's natural flow regime also includes chronic events such as flooding or extreme droughts, and these are required to maintain ecological complexity. Extreme flows (floods) are one of the key components found in a river's natural flow regime. Extreme flows are referred to as a "disturbance" when it causes significant loss of individuals from a community (Biggs *et al.*, 1999). The response of ecosystems/ organisms to extreme flows depends on the characteristics of the biota as well as the timing, magnitude and frequency of the extreme flow (Clausen *et al.*, 2004). Ecologically healthy aquatic ecosystems are dependent on natural hydrological disturbances. Extreme flows impact on spatial heterogeneity and temporal variability to the physical components of the system. This is reflected in the life history patterns, productivity and biodiversity of the biotic community. This natural disturbance creates the dynamic equilibrium (Naiman *et al.*, 1992). Disturbances such as floods increase the level of ecosystem complexity. An example would be chronic events, i.e. high intensity floods, which import material and woody debris during storm episodes. They shape the environment and cause alterations in channel morphology. Annual floods create freshly disturbed habitats for plant colonisation, increase the area of land under water and form travel routes to breeding sites (Franklin, 1992). Extreme flows are generally part of the long-term flow regime and, while they are usually short-term, they have a major effect on the ecosystem. Both seasonal flow variation and chronic events are vital for the long-term sustainability of aquatic ecosystems and need to be reflected in a river's flow regime.

A flow regime of any river reach is dependent on upstream hydrology and the overriding climatic drivers such as the day-to-day variations in temperature and precipitation. Additional variations in these drivers, caused by anthropogenically induced climate change, will undoubtedly alter a river's flow regime and thus impact upon the aquatic ecosystems upon which human society and aquatic biota are so dependent. This is particularly significant in South African rivers due to their inherent high variability in terms of quantity, frequency and timing of flows, thus making them more susceptible to small changes in climate.

2.4 Impacts of Climate Change on Aquatic Ecosystems

Anthropogenic climate change potentially has serious implications on aquatic ecosystems and will ultimately affect the supply and quality of freshwater lakes and rivers throughout the world (Chu *et al.*, 2005). In addition to the challenges posed by land use change, environmental pollution, water storage and diversion, aquatic systems are expected to soon begin experiencing the added stresses of global climate change (Poff *et al.*, 2002). Effects of change in the physical and chemical properties of the atmosphere present many uncertainties for future catchment management (Dolph *et al.*, 1992; Risser *et al.*, 1992). The direct effects of increasing greenhouse gases in the atmosphere on aquatic ecosystems is not known. The overall impacts of climate change on catchments are likely to be diverse (Dolph *et al.*, 1992). Ecosystems require some disturbance regime to maintain complexity, but in reality climate change may cause too much ecosystem disturbance, which may exceed the *ecosystem's resilience* (i.e. the ability of an ecosystem to recover) and thus permanently alter the aquatic ecosystem and reduce its ability to function and provide goods and services on which we as humans depend (Stanford and Ward, 1992).

2.4.1 Potential impacts of increasing temperatures on aquatic ecosystems

Climate change is expected, *inter alia*, to increase global and thus local air temperatures, accelerate the retreat of mountain glaciers, reduce Arctic and Antarctic sea ice and alter the frequency and intensity of climatic phenomena, especially those related to rainfall, from daily events to inter-seasonal ones such as the El Niño phenomenon (McGinn, 2002). Greenhouse gas induced warming, in some areas more than others, will lead to higher surface temperatures and greater potential evaporation, hence reduce soil moisture and result in increasingly frequent droughts (Hardy, 2003; Schulze, 2003). Results from recent Regional Climate Change Prediction Model (RCCPM) scenarios for South Africa substantiate many of these assumptions.

As a class of ecosystems, inland waters are vulnerable to climatic change and other pressures, owing to their small sizes and positions downstream from many human activities. Impacts of a warmer climate on inland waters are already being observed in many parts of the world. A trend observed in 26 lakes and rivers in the northern hemisphere shows that at present the lakes, on average, freeze 9 days later and ice break-up is 10 days earlier than they were 150 years ago as a result of a 1.8°C increase in air temperature (IPCC, 2001). Continued warming will alter the thermal structure of aquatic ecosystems and will impact upon the aquatic species which inhabit these waters. Individual aquatic species, including fish and invertebrates, have an optimum range of temperatures for growth and reproduction, i.e. their thermal habitat. Increased global temperatures will likely shrink thermal habitats for many aquatic species (Hardy, 2003). Warming could lead to changes in species composition and density, sex ratios of, for example, reptiles, stability and food web dynamics of aquatic ecosystems (Beisner *et al.*, 1997, cited in Hardy, 2003).

Increases in water temperatures as a result of climate change are projected to alter fundamental ecological processes and the geographic distribution of aquatic species. Rates of nutrient

removal/accumulations and primary production are also a function of water temperature, and these may well be altered by climate change. A changing climate may intensify threats to aquatic ecosystems. For example, a warmer climate may increase habitat fragmentation (Meyer *et al.*, 1999). Such impacts and threats may be ameliorated if species attempt to adapt by migrating to more suitable habitats. However, human alteration of potential migratory corridors may limit the ability of species to relocate, increasing the likelihood of species extinction and loss of biodiversity (Meyer *et al.*, 1999; IPCC, 2001; Poff *et al.*, 2002). This problem is exacerbated in the case of aquatic ecosystems, where many species are confined to the riparian zone of a stream, which makes migration laterally (i.e. from one river system to the next) impossible. Furthermore, many aquatic species are highly specialised, making them more susceptible to habitat alteration.

A warmer world does not only threaten the natural environment, but also the usefulness of the aquatic ecosystem in terms of its utilisation potential for anthropogenic activities. Climate change alterations in some streams may decrease the potential for irrigation abstractions and waste disposal. There may also be a reduction of the flush effect to remove human wastes if future flows were to decrease, with a decrease in flows possibly impairing ecosystem services (Hardy, 2003). This reduced flushing effect could lead to increased biological water quality problems, e.g. an increase in the presence of faecal contamination.

2.4.2 Potential impacts of changes in precipitation patterns on aquatic ecosystems

Changes in seasonal patterns of precipitation and runoff will alter hydrological characteristics of aquatic systems, affecting species composition and ecosystem productivity. Populations of aquatic organisms are sensitive to changes in the frequency, duration and timing of extreme precipitation related events, such as floods or droughts. Changes in the seasonal timing of snowmelt in areas where snow is a significant contributor to the hydrological regime, will alter streamflow patterns, potentially interfering with the reproduction of many aquatic species (Poff *et al.*, 2002). Anthropogenic climate change that alters dominant patterns of precipitation and runoff therefore presents a real threat to the structure and function of aquatic ecosystems, including rivers, lakes, wetlands and coastal systems (Meyer *et al.*, 1999).

Environmental variability (including flooding) plays a critical role in structuring aquatic and riparian ecosystems through mediating the directions and outcomes of ecological processes at multiple scales of hierarchical ecological organisation (Poff, 2002). A change in environmental drivers, such as climate, modifies the core of a given ecosystem. This in turn, modifies the relative outcomes of ecological processes, resulting in a change in ecological structure and function. This is the basic conceptual model for ecological response to environmental alteration, such as rapid climate change, where the regimes of one or more of the environmental drivers may be expected to change on a regional scale and thereby modify river ecosystems (Poff, 2002). Climate change has the potential to disrupt and even decrease aquatic ecosystem productivity and, as such, there is a need to establish methods which can be used to assess these impacts.

In this chapter the roles and benefits provided by aquatic ecosystems were investigated followed by a discussion on how the system's flow regime plays a critical role maintaining a healthy aquatic ecosystem. Finally, the potential impacts on aquatic ecosystems of climate change, via an increase in temperature and changes in precipitation patterns, were highlighted.

Ecological indicators are a tool commonly used in environmental assessments and their usefulness in climate change impact studies is discussed in the following chapter.

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CHAPTER 3 ECOLOGICAL INDICATORS: SOME GENERAL CONCEPTS AND THE SELECTION OF INDICATORS OF HYDROLOGIC ALTERATION

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3.1 Introduction

Anthropogenically driven climatic change may disrupt normal ecological functioning and thus compromise valuable ecosystem goods and services on which human society depends. There is a need to assess the impact of climatic change on aquatic ecosystems. Recent ecological research has developed methods of identifying, monitoring and managing the ecological integrity of aquatic environments through the use of ecological indicators (Fanelli, *et al.*, 2006). Ecological indicators are suitable for use in impact studies where one needs to determine how certain ecological components respond to a change in environmental conditions over an extended period of time. Ecological indicators have also been suggested as useful tools in environmental assessments (Manoliadis, 2001). However, ecological responses to change are often unknown and therefore difficult to assess either with, or without, indicators. Even so, the development and validation of such indicators on a national scale could help form sound environmental policies and thus facilitate better adaptation and preparation for potential environmental problems (Andreasen *et al.*, 2001). In this chapter the concept of ecological indicators, how they are selected and how they can be used in climate change impact studies, are reviewed.

3.2 What are Ecological Indicators?

Ecological indicators are measures used to describe the state of a nation's ecological status (Andreasen *et al.*, 2001). Indicators are used in many sectors of environmental science and generically they are seen as a distance measure from a goal, or target, against which aspects of policy performance should be assessed (Manoliadis, 2001). More specifically, however, an ecological indicator is a "characteristic of an ecosystem that is related to, or derived from, a measure of a biotic or abiotic attribute that can provide quantitative information on ecological condition, structure and function" (EPA, 2006).

Ecological indicators have numerous functions, but most importantly should inform the user easily and quickly of the state (health) of the environment. They can also be used to assess vulnerability, risk and damage to ecosystems, to monitor trends over time and to provide early signals of changes (Karr, 1991). It is of vital importance that ecological indicators detect and summarise patterns of ecosystems and show when environmental problems are occurring (Fanelli *et al.*, 2006).

There are two principal types of indicators, viz. condition indicators and stressor indicators.

- *Condition indicators* are biotic or abiotic characteristics of an ecosystem that can provide an estimate of the condition of an ecological resource with respect to some environmental value, such as ecosystem integrity.
- *Stressor indicators*, on the other hand, are characteristics that are expected to change the condition of a resource if the intensity or magnitude is altered (EPA, 2006).

Aquatic organisms and water quality are often used to indicate a river's health in aquatic ecosystem studies. For example, animals such as frogs are known as indicator species and if these specific species start to disappear, this indicates that the ecosystem's overall health and functionality may be

decreasing. In some cases water quality can also be used to indicate ecosystem health because it effectively integrates the full range of geomorphological, hydrological and biological processes (Hem, 1985). A change in water quality usually indicates a change in some aspect of the terrestrial, riparian, or in-channel ecosystem. Water temperature, a component which forms part of the generic term *water quality*, is easily measured and greatly affects the rate of chemical and biological processes, and it can initiate certain functions once the temperature is above or below a certain threshold. Stream temperature is a relatively sensitive indicator of riparian conditions and is controlled by climatic and atmospheric inputs (Naiman *et al.*, 1992). However, it is important to note that ecological functioning depends on many inter-related processes and not just on a single indicator such as water temperature.

No matter how good an indicator is, no single indicator can be expected to measure everything about the ecological health of an area. Thus, a suite of ecological indicators must be selected, in the first instance to encompass the phenomena of interest and, secondly, to correspond to stated policy goals and/or research and management questions related to these goals (Andreasen *et al.*, 2001). There are literally hundreds of both qualitative and quantitative indicators which can be used to illustrate ecosystem health and thus the selection of suitable ecological indicators is of vital importance.

3.3 On the Selection of Ecological Indicators

The use of ecological indicators relies on the assumption that the presence or absence of, and fluctuations in, these indicators reflect changes taking place at various levels in the ecological hierarchy, from genes to species and ultimately to entire regions (Noon *et al.*, 1999 cited in Dale and Beyeler, 2001). The problem with using ecological indicators is that there is no universal set of indicators that is equally applicable in all cases (Manoliadis, 2002). Therefore, the ideal suite of indicators should represent key information about ecosystem structure, function and composition. Appropriate indicators should deal with the complexity of ecological systems. There have been numerous attempts at developing criteria to select the most appropriate indicators for environmental projects (e.g. World Bank, 1999; Methratta and Link, 2006). However, one of the most comprehensive set of criteria to select the most suitable indicators has been developed by Dale and Beyeler (2001). They suggest the following criteria for indicator selection:

- *Ease of measurability*: The indicator should be straightforward and relatively inexpensive to measure. The metric needs to be easy to understand, simple to apply and, most important, be relevant.
- *Sensitivity to stresses on the system*: The ideal ecological indicator is responsive to stresses placed on the system by human actions, while also having limited and documented sensitivity to natural variation (Karr, 1991). While some indicators may respond to all of the more dramatic changes in the system, the most useful indicator is one that displays high sensitivity to a particular stress, thereby serving as an early indicator of reduced system integrity.
- *Response to stress in a predictable manner*: The indicator response should be unambiguous and predictable, even if the indicator responds to the stress by a gradual change. Resource managers may uncritically assume that indicators give unbiased estimates of the true biological condition, but this assumption is largely untested. The use of biased indicators could lead to ineffective and potentially damaging management (Cao and Hawkins, 2005). Ideally, there is some threshold response level at which the observable response occurs before a level of concern is reached.
- *Ability to be anticipatory, i.e. signify an impending change in key characteristics of the ecological system*: Change in the indicator should be measurable before substantial change in ecological system integrity occurs.

- *Be integrative, i.e. with the full suite of indicators providing a measure of coverage of the key gradients across the ecological systems (e.g. gradients across soils, vegetation types, temperature, space, time, etc.):* The full suite of indicators for a site should integrate across key environmental gradients. For example, no single indicator is applicable across all spatial scales of concern.
- *Have a known response to disturbances, anthropogenic stresses, and changes over time:* The indicator should have a well-documented reaction to both natural disturbance and to anthropogenic stresses in the system. Focal indicator species are often the only types of species that have a foundation of information large enough to indicate long-term trends and responses to change.
- *Have low variability in response:* Indicators should have a small range in response to particular stresses in order to allow for changes in the response value to be better distinguished from background variability.

All these criteria should be taken into account before the final indicators are selected. A major challenge is to derive a manageable set of indicators that meets these criteria and links closely to project objectives and environmental problems being addressed.

3.4 The Use of Ecological Indicators in Climate Change Impact Studies

There is a need to predict the potential impact of climate change on aquatic ecosystems as managers and policy makers require information regarding ecosystems conditions, trends and future status. However, ecological systems are inherently complex in being composed of many interacting biological and physical components. Predicting the impact of climate change on such complex systems is difficult, owing to issues regarding scale and not knowing exactly what to measure (Andreasen *et al.*, 2001).

Research should attempt to develop suitable indicators of ecosystem integrity for impending ecological change resulting from both natural variation and future anthropogenic activities. Furthermore, using a multidisciplinary approach along with performing ecosystem analysis at an appropriate scale will, hopefully, result in robust techniques for ecosystem monitoring and evaluation (Debusk *et al.*, 2001).

3.5 Indicators of Hydrologic Alteration: An Approach to Assessing Eco-Hydrological Change

The so-called Indicators of Hydrologic Alteration, or IHA (e.g. Richter *et al.*, 1996; 1997; Taylor, 2006), are commonly used in eco-hydrological studies for assessing quantitatively the characteristics of natural and altered hydrological regimes. The power of the IHA method is that it can be used to summarise long time series of daily hydrological observations or simulated output into a much more manageable series of ecologically relevant hydrological parameters. The IHA consists of a total of 67 statistical parameters used to describe hydrological regimes (The Nature Conservancy, 2005). The IHA indicators represent the five components of the streamflow regime, *viz.*

- Magnitude,
- Frequency,
- Duration,
- Timing, and
- Rate of change.

What follows below is a summary of the descriptions of the five components of a flow regime, as given by Richter *et al.*, 1996; 1997 and Taylor (2006).

- The *magnitude of the monthly means of daily flows* represents average daily flow conditions for a specific month and defines such habitats attributes as wetted area within a channel or the availability of aquatic habitat area for that month. Generally, the greater the flow magnitude, the greater the availability of habitat area. The degree to which the means of flows of a given month vary from year to year indicates the inter-annual variation of streamflow conditions, which in the IHA is defined by the Coefficient of Dispersion.
- The *magnitude and duration of extreme annual conditions* are a measure of different environmental disturbances, or stresses, such as levels of inundation or desiccation. The durations comprise of the 1 day, 3 day, 7 day (weekly), 30 day (monthly) and 90 day (seasonal) extremes. The 1 day events are the maximum and minimum daily streamflow values that occur in any given hydrological year, and the multi-day events are the highest and lowest multi-day means of flow occurring in any given hydrological year. These values are then averaged for the years that are being analysed. As a measure of inter-annual variation, the Coefficient of Dispersion can be calculated from each year's values for each duration (e.g. 1 day, 3 day...90 day) of extreme annual maximum and minimum conditions.
- The Julian date of the 1 day maximum and minimum flow events represents the *timing of the annual extreme conditions* within annual cycles and provides a measure of the seasonal nature of environmental stresses, or the likelihood of mortality associated with flow extremes such as droughts or floods. The timing of these flows can also determine whether certain life cycle requirements are met.
- The *frequency of conditions* during which the magnitude of streamflows exceeds an upper threshold (high flow) or falls below a lower threshold (low flow) within a hydrological year, and the *average duration of such occurrences* together reflect the pulsing behaviour of the streamflow regime within a given year. The frequency of occurrence of these high and low pulses can influence the reproduction and mortality rates and thereby influence population dynamics of aquatic habitats.
- The *rate and frequency of change in conditions* measures the number and average rates of both positive and negative changes (i.e. reversals) in streamflows between consecutive days. These changes in the hydrograph trend indicate the intra-annual fluctuation of the streamflow regime and can also be tied to the stranding of certain aquatic organisms along the water's edge.

3.6 Selection of Flow Indicators

This research uses a subset of the 67 IHA indices to determine how the selected indicators may change under conditions of projected climate change. This subset, which focuses solely on the magnitude and duration of flows, was selected for its ease of measurability and lack of data, at the time of completing this research (December 2008), to be able to map some of the more complex indicators. **Table 3.1** summarises the flow indicators used in this research project.

3.7 Magnitudes of Flows

In order to spatially analyse how the indicators which measure the magnitude of flow may change under conditions of projected climate change, a number of methods and datasets were used. First, the *ACRU* model was used to simulate the eco-hydrological responses for the 5 838 hydrologically interlinked and cascading Quinary Catchments which constitute the defined southern African study region. The *ACRU* model was run with 20 years of daily climate records for a

Table 3.1 Hydrological indicators used in this study, their derivation and source of reference, with notation for indicators as in Olden and Poff, 2003 (After Taylor, 2006)

Symbol	Unit	Definition	Reference
Magnitude of flow events			
Average flow conditions			
M _{A1}	m ³ .s ⁻¹	Mean monthly flow for October	Richter <i>et al.</i> (1996; 1997)
M _{A2}	m ³ .s ⁻¹	Mean monthly flow for November	
M _{A3}	m ³ .s ⁻¹	Mean monthly flow for December	
M _{A4}	m ³ .s ⁻¹	Mean monthly flow for January	
M _{A5}	m ³ .s ⁻¹	Mean monthly flow for February	
M _{A6}	m ³ .s ⁻¹	Mean monthly flow for March	
M _{A7}	m ³ .s ⁻¹	Mean monthly flow for April	
M _{A8}	m ³ .s ⁻¹	Mean monthly flow for May	
M _{A9}	m ³ .s ⁻¹	Mean monthly flow for June	
M _{A10}	m ³ .s ⁻¹	Mean monthly flow for July	
M _{A11}	m ³ .s ⁻¹	Mean monthly flow for August	
M _{A12}	m ³ .s ⁻¹	Mean monthly flow for September	
M _{A13}	-	Mean annual flow	
M _{A14}	-	Coefficient of Dispersion of M _{A1} ,	
M _{A15}	-	Coefficient of Dispersion of M _{A2}	
M _{A16}	-	Coefficient of Dispersion of M _{A3}	
M _{A17}	-	Coefficient of Dispersion of M _{A4}	
M _{A18}	-	Coefficient of Dispersion of M _{A5}	
M _{A19}	-	Coefficient of Dispersion of M _{A6}	
M _{A20}	-	Coefficient of Dispersion of M _{A7}	
M _{A21}	-	Coefficient of Dispersion of M _{A8}	
M _{A22}	-	Coefficient of Dispersion of M _{A9}	
M _{A23}	-	Coefficient of Dispersion of M _{A10}	
M _{A24}	-	Coefficient of Dispersion of M _{A11}	
M _{A25}	-	Coefficient of Dispersion of M _{A12}	
M _{A26}	-	Coefficient of Dispersion of M _{A13}	
Low flow conditions			
M _{L1}	-	Ratio of baseflow volume to total volume (Alt-BFI)	Hughes, Hannart and Watkins (2003)
Duration of flow events			
Low flow conditions			
D _{L1}	m ³ .s ⁻¹	Annual minimum 1 day average flow	Richter <i>et al.</i> (1996; 1997)
D _{L2}	m ³ .s ⁻¹	Annual minimum 3 day average flow	
D _{L3}	m ³ .s ⁻¹	Annual minimum 7 day average flow	
D _{L4}	m ³ .s ⁻¹	Annual minimum 30 day average flow	
D _{L5}	m ³ .s ⁻¹	Annual minimum 90 day average flow	
D _{L6}	-	Coefficient of Dispersion in D _{L1}	
D _{L7}	-	Coefficient of Dispersion in D _{L2}	
D _{L8}	-	Coefficient of Dispersion in D _{L3}	
D _{L9}	-	Coefficient of Dispersion in D _{L4}	
D _{L10}	-	Coefficient of Dispersion in D _{L5}	
High flow conditions			
D _{H1}	m ³ .s ⁻¹	Annual maximum 1 day average flow	
D _{H2}	m ³ .s ⁻¹	Annual maximum 3 day average flow	
D _{H3}	m ³ .s ⁻¹	Annual maximum 7 day average flow	
D _{H4}	m ³ .s ⁻¹	Annual maximum 30 day average flow	
D _{H5}	m ³ .s ⁻¹	Annual maximum 90 day average flow	
D _{H6}	-	Coefficient of Dispersion in D _{H1}	

D _H 7	-	Coefficient of Dispersion in D _H 2	Richter <i>et al.</i> (1996; 1997)
D _H 8	-	Coefficient of Dispersion in D _H 3	
D _H 9	-	Coefficient of Dispersion in D _H 4	
D _H 10	-	Coefficient of Dispersion in D _H 5	

- Baseline (i.e. historically observed) Climate (1971-1990), for
- Present Climate (1971-1990) from the ECHAM5/MPI-OM GCM (hereafter abbreviated as ECHAM5), for an
- Intermediate Future Climate (2046-2065) from ECHAM5, and a more
- Distant Future Climate (2081-2100) from ECHAM5.

The above climate scenarios, together with the datasets described in **Chapter 9**, were used as an input into the *ACRU* model. The 20 year baseline scenario from 1971 to 1990, which uses historically recorded climate variables, was used as the reference in order to gain an insight into how well ECHAM5 was simulating the “present” climate scenario for the same period of time. After running the model using climatic input from all the above scenarios, both individual subcatchment runoff and accumulated streamflow values were extracted from the model’s output and mapped in order to interpret the spatial patterns across southern Africa of the indicators which describe the magnitude of flow. Simulated runoff from individual subcatchments (*ACRU* variable name = SIMSQ) is an output from the *ACRU* model and is defined as the sum of stormflows and baseflows from only the subcatchment in question, excluding any contributions from upstream catchments (Schulze, 1995). The *ACRU* model outputs this variable in millimetre (mm) equivalents and it is subsequently converted to cubic metres (m³) using catchment area. Accumulated streamflow (*ACRU* variable name = CELRUN) is also an output from the *ACRU* model and is defined as the total summed streamflow from a catchment, but also including any contributions from upstream catchments (Schulze, 1995). The *ACRU* model outputs this variable in millimetre (mm) equivalents and, similarly to individual subcatchment runoff, it is converted to cubic metres (m³) using the total upstream catchment area.

The monthly and annual means (Indices M_A1 - M_A13 in **Table 3.1**) were extracted for both individual subcatchment runoff and accumulated streamflows for the 5 838 Quinary Catchments. The individual runoff and accumulated streamflow output from *ACRU* was then subjected to a statistical analysis to determine the 25th, 75th and median values for all Quinary Catchments. Using the result of this analysis the Coefficient of Dispersion (CoD), an indicator of inter-annual flow variability, was calculated using **Equation 3.1** given below:

$$\text{CoD} = \frac{75\text{th Percentile} - 25\text{th Percentile Value}}{\text{Median of Values Across all Years of Record}} \quad [3.1]$$

The CoD uses the median value across all years of record within a climate scenario, rather than the mean, as the mean value is often skewed by extreme events in the “highly variable” river systems which are found in South Africa (Taylor, 2006). Streamflow is naturally variable and information is also needed about the variation within data samples and thus the CoD was calculated to determine how the variability regarding the magnitude of flow is likely to change under projected conditions of climate change. The CoD of subcatchment runoff and accumulated streamflows was determined for indices M_A1 - M_A13 (**Table 3.1**). The results for this analysis are given in **Chapter 12**.

3.8 Durations of Flow Events

As was the case in **Section 3.7**, the *ACRU* model was used to simulate eco-hydrologically critical flow responses of different durations for the 5 838 Quinary Catchments which constitute the southern Africa study region, using the same climate scenarios and time periods. However, unlike magnitudes of flow events, the daily accumulated streamflow output from *ACRU* was then used to calculate the averages of the annual minimum (D_{L1} - D_{L5} in **Table 3.1**) and maximum (D_{H1} - D_{H5} in **Table 3.1**) 1, 3, 7, 30 and 90 day accumulated streamflow values. The duration of flow events is the period of time associated with a specific water condition (Richter *et al.*, 1996). The durations used in this research are based on the recommended durations from the developers of the IHA and attempt to represent natural cycles of short duration (1 day and 3 day), of weekly (7 day), monthly (30 day) and seasonal (90 day) extremes (The Nature Conservancy, 2005). The 1 day events are the maximum and minimum daily streamflow values that occur in any given year and the multi-day events are, by the same token, the highest and lowest multi-day means of flows occurring in any given year (Taylor, 2006).

Similarly to the magnitude of flow events, the inter-annual CoD was also calculated for the annual minimum and maximum 1, 3, 7, 30 and 90 day average accumulated streamflow values using the method outlined in **Section 3.7**. The results for this analysis are presented in **Chapter 12**.

3.9 References

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CHAPTER 4 WATER TEMPERATURE

K.R. Barichievsky and R.E. Schulze

4.1 Introduction

It has already been alluded to, that anthropogenically forced climate change has serious implications for aquatic ecosystems and may ultimately affect the supply to, and quality of, freshwater lakes and rivers throughout the world (Chu *et al.*, 2005). There is, therefore, a need to assess the impact of climatic change on aquatic ecosystems. In this chapter the importance of water temperature as an eco-hydrological indicator is investigated, along with the factors which affect water temperature and thermal regimes. Subsequently, the projected impact of climate change on water temperature is explored and selected methods on how to model water temperature in lotic environments are reviewed.

4.2 The Importance of Water Temperature

Water temperature in streams and rivers is an important attribute of water quality and it controls the overall health of freshwater ecosystems (Morrill *et al.*, 2005). Except for birds and mammals, all organisms associated with freshwater ecosystems are *poikilothermic*, i.e. they are unable to control their body temperatures and, therefore, their body temperatures are the same as that of the ambient water temperatures (Dallas and Day, 2004). Essentially aquatic organisms are therefore inextricably linked to the ambient water temperature in which they exist.

There are a number of ways in which water temperature impacts upon aquatic ecosystems and associated aquatic biotas. The most obvious effect of stream water temperatures on aquatic organisms is in their growth rate, behaviour, survival and development (Elliot and Hurley, 1997). Aquatic organisms have a specific range of temperatures within which they function optimally. Once outside this temperature range, vital functions such as reproduction and metabolism may be hindered, or may not occur whatsoever.

Water temperature does not only affect aquatic organisms directly, but also influences their habitat and, in fact, determines the limits of thermal habitat space for many aquatic organisms (Erickson *et al.*, 2000). The minimum and maximum points in this temperature range are known as the lethal limits and vary from species to species (Dallas and Day, 2004). Water temperature also influences many chemical and biological processes in river systems. This makes water temperature a key indicator in aquatic ecosystem studies (Webb, 1987; Erickson *et al.*, 2000; Caissie *et al.*, 2001; Mosheni *et al.*, 2002; Rivers-Moore, 2003), as well as being important to the kinetics of chemical reactions, the solubility of gases and the toxicity of some elements within an aquatic environment (Erickson *et al.*, 2000). In the following section the effects which temperature variations exert on aquatic biota and ecosystems will be investigated.

4.3 The Effects of Temperature Variation on Aquatic Biotas and Ecosystems

All lotic (i.e. running waters, e.g. rivers) and non-lotic (i.e. standing waters, e.g. reservoirs) systems have natural thermal regimes which mimic seasonal temperature changes, i.e. water temperatures tend to be highest in late summer and coldest in late winter. Aquatic organisms are adapted so that seasonal changes in water temperatures act as cues for various stages of development such as the timing of migration, spawning and emergence. Natural thermal characteristics of lotic systems are

dependent on the interaction between hydrological, climatological and structural features of the region and catchment (Dallas and Day, 2004). Anthropogenic impacts such as land use changes and climate change have already begun to alter this natural thermal regime in catchments around the world. For example, the construction of large reservoirs has played an enormous role in altering both the flow and thermal regimes of rivers downstream of their walls. Deforestation is another process which can greatly alter the thermal regime of a stream and thus influence the integrity of that same ecosystem. Studies show that stream temperatures increase after logging, largely because of the increased exposure of the stream surface to solar radiation (e.g. Cafferata, 1990).

Changes in water temperature regimes may have an effect on an organism, a species or an entire community. Increased variations in water temperature may expose organisms to potentially lethal or sub-lethal conditions. Temperature variations, in turn, affect the aquatic biota in regard to physiology, life cycle and community structure (Dallas and Day, 2004). Most temperature variation in aquatic ecosystem occurs during summer due to climatic and hydrological factors and it is important to note that temperature varies both temporally (e.g. daily and seasonally) and spatially along river reaches (Caissie *et al.*, 2001).

In general, water temperatures in streams will be rising due to anthropogenic impacts (e.g. global warming, deforestation) and, as such, the focus will be on the impacts of higher temperatures on aquatic biotas. High stream temperatures can have adverse effects on fishery resources by limiting habitats and can, in cases, result in fish mortality. Poikilothermic organisms are highly susceptible to changes in water temperature because an increase in 10°C leads to a doubling in the metabolic rate (Hellawell, 1986). An increase in water temperature decreases oxygen solubility and may increase the toxicity of certain chemicals as well as increasing the stress on aquatic organisms. As a result, even if food is abundant at higher temperatures, decreases in dissolved oxygen (DO) may stress certain aquatic organisms metabolically, thereby increasing their susceptibility to disease (Dallas and Day, 2004). It could also lead to an augmented distribution of water-borne diseases such as bilharzia and malaria and thus have serious social and financial implications.

In order to address potential problems associated with rising stream temperatures, resource managers need to incorporate stream temperature objectives in their operations models and management decisions. This requires the ability to predict stream water temperature. Because the prediction will be used in daily operating decisions, the prediction must meet the following specific requirements, viz. it must be

- quick,
- accurate,
- easy to use, and
- spatially and temporally consistent with the operations models.

To incorporate stream temperature in the operations model, the normal operating policies are simulated and the stream temperature needs to be predicted (Neumann *et al.*, 2003).

4.4 Factors Affecting Water Temperature and Thermal Regimes

Ambient water temperature has been shown to be one of the most important factors affecting the success of aquatic life. Land use activities, water abstractions, streamflow alterations, dam construction and associated water releases, as well as natural factors, all affect a stream's water temperature within a catchment.

Dallas and Day (2004) have summarized the factors which influence the thermal characteristics of lotic systems into three major divisions related to hydrological, climatological and structural features. These major features and the associated factors which affect thermal regimes of rivers are summarised in **Table 4.1**.

Table 4.1 Major factors affecting the thermal regime of rivers (after Day and Dallas, 2004)

Feature	Factor
Hydrological	Source of water (snowmelt, dam outlet)
	Groundwater contribution
	Flow rate and discharge
	Water volume and depth
	Turbidity
Climatological	Latitude and altitude of river
	Cloud cover
	Wind speed
	Vapour pressure and relative humidity
	Precipitation events
	Incoming solar radiation and air temperature
Structural	Catchment and river topography
	Vegetation cover and characteristics
	Channel form

The hydrological feature in **Table 4.1** groups all flow related factors which influence water temperature. With particular reference to South Africa, the source of water is mostly from surface runoff, groundwater contributions and dam releases and rarely includes snowmelt as a source. Thus the interactions between surface and groundwater, along with dam releases, are critical to the thermal regime of South African rivers. Turbidity, along with flow characteristics such as flow rate, volume and water depth also falls within hydrological features which influence water temperature and, as a consequence, needs to be carefully considered when examining water temperature.

The climatological feature in **Table 4.1** groups all meteorological and climatological parameters together. Incoming solar radiation and air temperature play the most critical roles in determining the ambient water temperature in aquatic environments (**Figure 4.1**).

At the catchment scale, differences are driven by variations in climate, geography, topography and vegetation (Poole and Berman, 2001). At a river scale, variation occurs longitudinally down a river system, with headwaters typically at lower temperatures than those of water in lowland areas. Maximum temperatures increase downstream (Ward, 1985) while the maximum range in temperature is often found in the middle reaches of a river (Vannote and Sweeney, 1980). The temperature of larger rivers and smaller streams is also influenced by the surrounding landscape and reflects the characteristics and condition of the stream and its valley (Beschta *et al.*, 1987), with the alteration of aquatic environments generally causing an increase in water temperature. It is for these reasons that structural factors (**Table 4.1**) need to be considered when investigating the thermal regime of rivers and streams. Structurally based factors tend to have more impact on thermal regimes at small (river reach) scale. For example, shading and sheltering can greatly influence water temperature at small scales and many environmental sectors, including forestry, recognise the need to maintain riparian trees in order to provide direct shade and prevent elevation of water temperature.

Anthropogenically induced changes of catchment and atmospheric conditions can also influence the temperature regime of lotic systems by processes such thermal pollution, timber harvesting and climate change (Cassie *et al.*, 2001). Hostetler (1991) found that water temperature could be

increased by 8°C within a distance of 1.3 km of where trees had been removed from the river banks, mainly due to a decrease in water surface shading (Caissie *et al.*, 2001).

It is apparent that many factors need to be considered when investigating, or estimating, water temperature. It is even more evident that estimating water temperature at large scale is difficult or even impossible if one is required to account for all the factors which influence ambient water temperature. By ranking factors which influence water temperature by how sensitive daily mean water temperature is to changing these factors, one is able to understand which factors drive water temperature in lotic systems (**Figure 4.1**).

Figure 4.1 illustrates that air temperature above the stream surface is the most important factor in increasing water temperatures, followed by relative humidity, shading and streamflow. Thus, in order to estimate water temperature, these more influential factors need to be quantified. These variables can be divided into drivers (e.g. solar radiation) and buffers (e.g. flow volume) and in terms of modelling buffers are easier to manage.

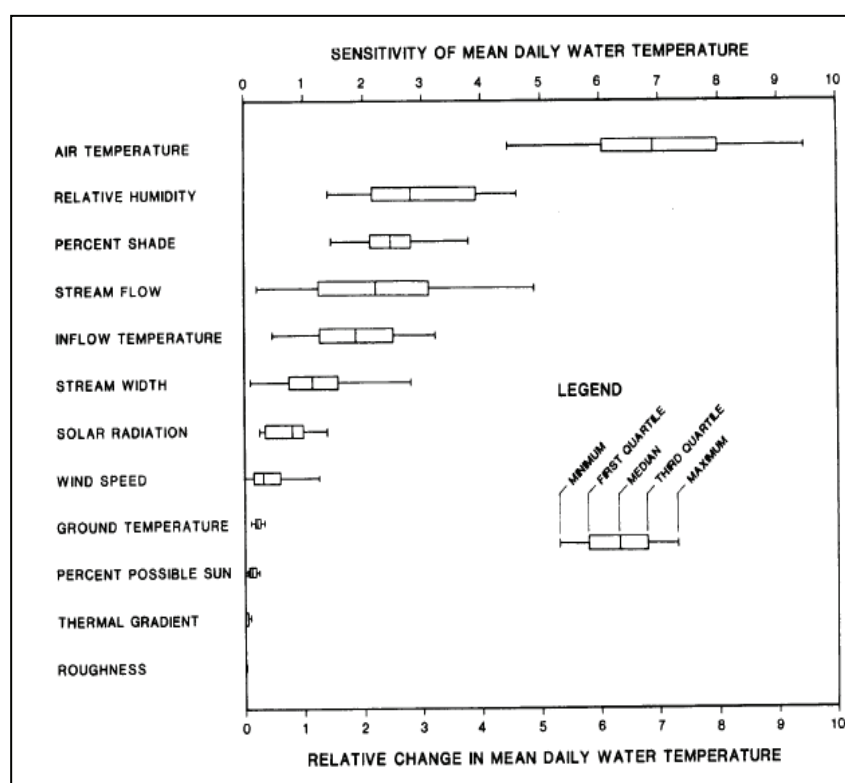


Figure 4.1 Factors that influence stream temperature (Bartholow, 1989)

4.5 Water Temperature and Climate Change

The effects of a change in water temperature may be direct, including thermal discharges, or indirect, including land use changes, irrigation return flows, flow modifications (such as river regulation), inter-basin water transfers, modification to riparian vegetation and global warming (Dallas, 2008). The implications of projected climatic changes on water resources and on natural ecosystems are of great environmental concern (Avila *et al.*, 1996). In the post-industrial era, scientists generally use the term climate change in the manner defined by the United Nations Framework Convention on Climate Change (UNFCCC), in that it is a change of climate that is attributed directly or indirectly to human

activity that alters the composition of the global atmosphere and which is, in addition to natural climate variability, observed over a prolonged and comparable period of time (Hardy, 2003).

The main response to the alteration of the atmospheric composition (i.e. increase in greenhouse gases) includes changes in temperature which, in turn, results in changes in precipitation attributes and hence in entire climatic systems (Schulze, 2003). The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2007) projects that global average temperatures by 2100 will be between 1.8 and 4.0°C higher than the 1980 - 2000 average (i.e. the best estimate, with a likely range of 1.1-6.4°C). Sea levels are projected to rise 0.18-0.59 m by 2100. Furthermore, it is *very likely* that temperature extremes at the high end, prolonged heat waves and heavy precipitation events will continue to become more frequent (EEA, 2007).

Anthropogenic climate changes and their likely impacts, as summarised above, have the potential for serious implications on aquatic ecosystems and could ultimately affect the water supply and quality of freshwater lakes and rivers throughout the world (Chu *et al.*, 2005). A rise in air temperatures is expected to increase stream temperatures (Mohseni *et al.*, 1999). Increases in water temperatures as a result of climate change will alter fundamental ecological processes (e.g. reproduction, migration and metabolism) as well as the geographic distribution of aquatic species. This may have a profound effect on water quality and the availability of habitat for aquatic organisms, including fish (Bogan *et al.*, 2006). Stream temperatures are, therefore, of great ecological importance, especially under conditions of a projected warmer climate (Mosheni *et al.*, 2002). A sound knowledge of river water temperature modelling is, consequently, essential in the management of aquatic resources and in addressing climate change issues (Caissie *et al.*, 2001).

4.6 Modelling Water Temperature

Modelling water temperature in lotic systems is far more difficult than in open water systems. According to Handcock *et al.* (2006), a stream is a more complex environment than an impoundment because it is usually much smaller and its temperatures are often not resolved at the spatial resolution as those in impoundments. Streams often have a complex morphology of braided channels, islands and in-stream rocks, and they vary greatly in hydrological and hydraulic characteristics such as inputs from groundwater, water depth, water velocity and turbulence fluctuations. They also vary in the amount of bank vegetation present and the percentage of shading, which influence the amount of incoming solar radiation on streams.

Along with experimental approaches, the prediction of the long term responses of aquatic ecosystems to climate change requires the use of models (Avila *et al.*, 1996). There are two major approaches to modelling water temperature which are summarised below, *viz.*

- Deterministic, i.e. process based, approaches and
- Statistical approaches.

4.6.1 Deterministic approaches

Deterministic approaches focus on creating a conceptual energy balance between all the factors which influence water temperature. This approach is essentially a cause and effect relationship between site conditions and meteorological parameters and their influences on water temperatures (Caissie *et al.*, 2001). In **Table 4.2** the advantages and disadvantages of using deterministic approaches to modelling water temperature are summarised. A study undertaken by Huguet *et al.* (2008) which attempts to estimate high river temperatures for future decades used the CALNUT

model to compute a complete temperature series for a site which had an unreliable historical data series. The CALNAT model (**Equation 4.6.1**) calculates the temperature in a point of the river using a deterministic approach, integrating the equation of the temperature evolution (cf. Gras, 1969):

$$\frac{\partial T}{\partial t} + U \frac{\partial T}{\partial x} = \frac{\partial}{\partial x} \left(K \frac{\partial T}{\partial x} \right) + \frac{1}{\rho CH} (SR + AR - WR - C - E) \quad [4.6.1]$$

where

U = river velocity,
 K = thermal diffusivity along the river,
 ρ = mass of water per unit volume,
 C = specific heat capacity of water, and
 H = depth of river thermal inertia.

The five thermal fluxes SR , AR , WR , C and E are caused by solar radiation, atmospheric radiation, water radiation, wind convection and evaporation, respectively (Huguet *et al.*, 2008). The output from the model was from 11 stations which had reliable historical data was combined with the unreliable data from the site in question, in order to identify trends in the historical temperature records.

The CALNUT model is good example of a deterministic type approach to estimating water temperature and uses many input parameters to estimate water temperature at a single point of interest.

4.6.2 Statistical approaches

Statistical approaches relate water and air temperatures, since both are responding to similar energy balance components. When applying statistical regression type models the timing of the event is not particularly important (Caissie *et al.*, 2001). In **Table 4.2** the advantages and disadvantages of using a statistical approach to modelling water temperature are summarised. One such approach, developed by Mohseni *et al.* (1998), uses an S-shaped log function derived from daily air temperatures (**Equation 4.6.2**) to estimate stream temperature:

$$Ts = \mu + \frac{\alpha - \mu}{1 + e^{\gamma(\beta - Ta)}} \quad [4.6.2]$$

where

Ts = the estimated stream temperature,
 Ta = the air temperature measured at or near the stream gauging site,
 A = the estimated maximum stream temperature,
 μ = the estimated minimum stream temperature,
 γ = a measure of the steepest slope of the logistic function, and
 β = the air temperature at the inflection point (or curve midpoint).

Compared to the deterministic CALNUT model (**Section 4.6.1**) this statistical approach is simpler with far fewer input parameters, making it more attractive for large scale investigations into stream temperature estimation.

Linear correlation between water and air temperature falls within the statistical approach and it can be applied at large scale with few input parameters and this approach is described in greater detail in **Section 4.8**.

Table 4.2 Comparison between deterministic and statistical approaches to modelling water temperature (*after* Caissie *et al.*, 2001)

Approach	Advantages	Disadvantages
Deterministic	Well adapted to effluent type problems (mixing temperatures)	High complexity of model development and application
	Usually scenario based problems, with many parameters, e.g. solar radiation, wind speed	Large number of input parameters, which can lead to calibration problems
	Cause and effect water temperature modelling	Data often unavailable for study area
	Can aid in management decisions	Applied over very small areas
Statistical	Requires few input parameters	Over simplistic
	Generally used in simple applications	Generally based on one parameter
	Shows good results with air temperatures as sole input	Generally not as accurate as deterministic methods
	Well adapted to climate change studies, as GCMs simulate air temperature better than other climate variables (Lau <i>et al.</i> , 1996)	Based on the assumption that air and water temperatures are highly correlated throughout the study area
	Can be applied over a large area	
	Large datasets availability from climate stations	

4.7 Modelling Water Temperature Using Climate Change Scenarios

Modelling water temperature when using climate change input narrows the choice of approach which can be applied, owing to the limited range of output variables from GCMs. Thus, in order to estimate water temperature as an eco-hydrological indicator, statistical methods with their more limited input requirements are far more attractive to use than deterministic approaches. Linear regression models of stream temperature versus air temperatures are attractive for climate change impact studies because only one input variable, *viz.* air temperature, is used and General Circulation Models (GCMs) simulate this variable better than other climate variables (Lau *et al.*, 1996). In studies of the potential effects of global climate change on freshwater ecosystems, water temperature has been shown to be a primary factor (Mohseni and Stefan, 1999). Linear regression models using air temperatures as a surrogate for stream temperature have been applied successfully under various climate change scenarios, for example, doubling of atmospheric CO₂ (Mohseni and Stefan, 1999). One of the most common approaches to modelling water temperature under climate change thus uses input of air temperature as the primary input in a linear correlation analysis. Webb and Nobilis (1997) examined the relationship between monthly mean air and water temperatures for a small catchment in Austria over a time period of 90 years, and found a significant relationship between monthly water and air temperatures.

4.8 Linear Correlation between Water and Air Temperatures

The goal of regression models is to fit a set of data with an equation, the simplest being a linear regression equation (Neumann *et al.*, 2003). Research has shown that there is a strong correlation between stream and air temperatures between 0 and 25°C and that linear regression models can indeed be used to determine stream water temperatures from daily air temperatures (Morrill *et al.*, 2005). Furthermore there is, intuitively, a statistical linear correlation between air and water temperatures (Mohseni and Stefan, 1999) and it has been shown that air temperature can be a good and reliable indicator of stream temperature across a wide range of environmental settings, especially at weekly and monthly time scales in which temperature extremes are averaged and smoothed (Erickson *et al.*, 2000).

Pilgrim *et al.* (1998) used data from 39 Minnesota streams and found a near-linear relationship between stream and air temperatures for weekly and monthly data, but this relationship correlated less well at the daily time step. In a similar study, Webb (1987) found a more or less 1:1 relationship between weekly and monthly averages of stream and air temperature for 36 streams in the United Kingdom. Thus the temporal scale selected for the linear correlation between water and air temperatures is extremely important and care needs to be taken to ensure the correct temporal scale is used to match the nature of the investigation. Developing a linear regression model between water and air temperatures as also been attempted in South Africa. Rivers-Moore *et al.* (2005) developed a linear regression model for estimating maximum water temperature from data recorded over a period of 33 months at nine sites within the Sabie Catchment, which is situated in the Mpumalanga Province, South Africa. The model uses locally calibrated coefficients to estimate maximum water temperature with **Equation 4.8.1**, viz.

$$WT_{max} = 2.425 + 0.977 AT_{mean} \quad [4.8.1]$$

where

WT_{max} = the daily maximum water temperature, and
 AT_{mean} = the mean daily air temperature (Rivers-Moore *et al.*, 2005).

This equation has been found to robust and has been used in other climatic areas, including catchments located in the Eastern Cape.

By developing a predictive relationship between only air temperature and stream temperature it is implicitly assumed that air temperature is the most influential factor in determining stream temperature (Morrill *et al.*, 2005), and this has been shown to be the case in **Figure 4.1**. Factors such as stream boundaries, groundwater inflows, dam releases and thermal pollution obviously influence the linear fit between water and air temperature and the influences of these factors therefore need to be carefully considered when using a linear correlation approach to modelling water temperature as an eco-hydrological indicator. A good correlation between water and air temperatures can be achieved if the water in the stream under investigation is considered to be well mixed in both vertical and transverse directions, and perfect mixing is typically assumed when using statistical linear correlation. On the other hand, poor correlations between water and air temperatures can be caused by dam releases, groundwater inflows, unique local climates, industrial activity, shading, sheltering and deforestation (Erickson *et al.*, 2000).

In this chapter the use of water temperature related indicators in climate change impact studies investigated. The concepts surrounding the modelling of water temperature using deterministic and stochastic approaches was also introduced. It concluded that employing linear correlation between water and air temperatures is the most effective method of modelling water temperature using climate change scenarios at a large spatial scale. The following chapter introduces the Thukela Catchment, on which climate change impacts on water temperature indicators were computed.

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CHAPTER 5 THE THUKELA CATCHMENT: DESCRIPTION OF THE CASE STUDY AREA FOR THE ASSESSMENT OF CLIMATE CHANGE ON WATER TEMPERATURE

R.E. Schulze, D.J.M. Dlamini and M.J.C. Horan

5.1 Location and Background

The Thukela Catchment, which extends latitudinally from 27°25' to 29°24'S and longitudinally from 28°58' to 31°26'E in South Africa's province of KwaZulu-Natal (**Figure 5.1**), covers an area of 29 036 km². The Thukela River derives its name from an isiZulu word which means 'to startle', as its waters thunder downstream in flood. The Thukela Catchment is one of South Africa's 19 designated Water Management Areas (**Figure 5.1**), the water resources of which will eventually be managed by its own Catchment Management Agency (CMA). As one of the selected UNESCO-HELP (*Hydrology for the Environment, Life and Policy*) basins, wide-ranging research into facets of integrated water resources management is undertaken. The Thukela is characterised by its diversity - in physiography, climate, soils, land use and in its socio-economic status, for within the Catchment first world commercial agriculture is practised in juxtaposition with third world subsistence agriculture, and the nation's most water-rich Primary Catchment simultaneously displays areas of vast water poverty.

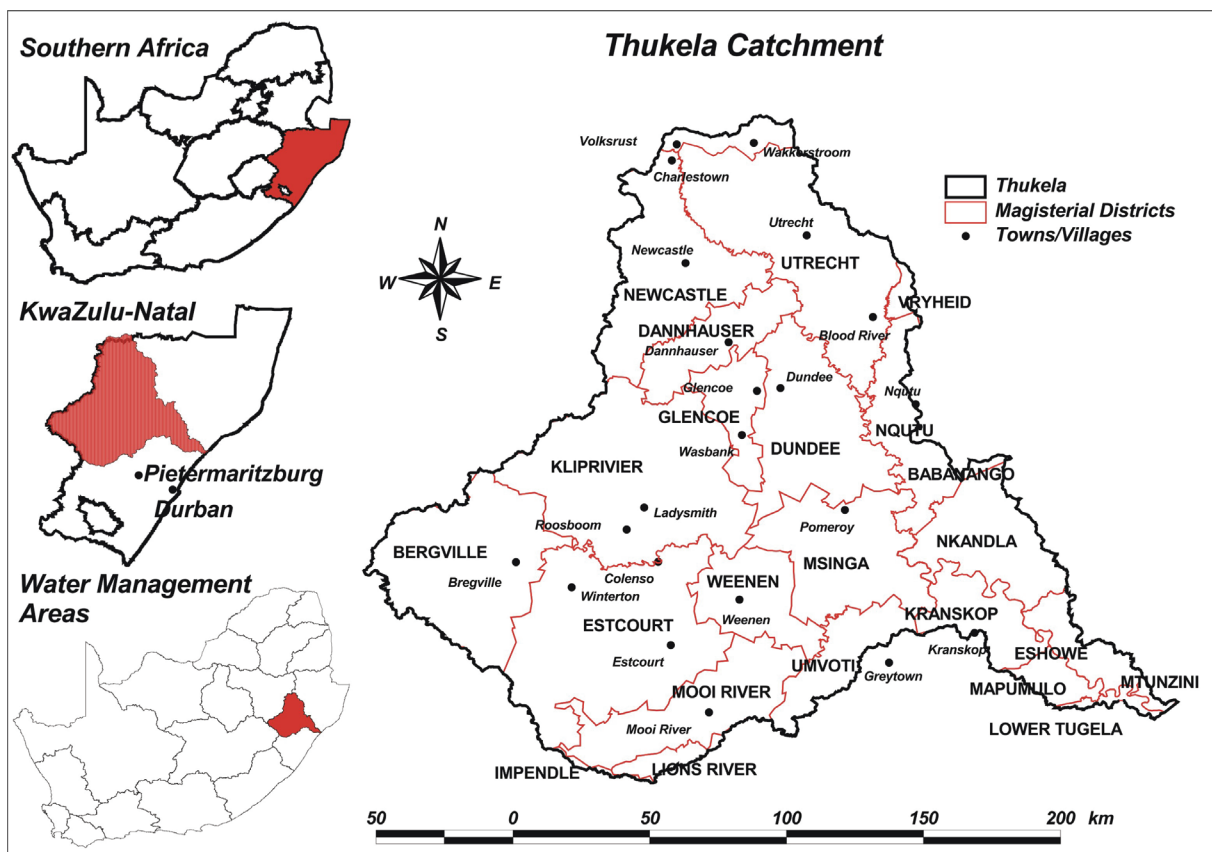


Figure 5.1 Location of the Thukela Catchment in relation to KwaZulu-Natal province, designated Water Management Areas in South Africa, magisterial districts and major towns within the Catchment (Schulze *et al.*, 2005)

5.2 Physiography

The Thukela River has its source in the 3 300 m altitude Drakensberg mountain range in the west of the Catchment (**Figure 5.2**). The Drakensberg is a declared World Heritage Site. The Thukela then flows eastward from a steep escarpment across low mountains of high relief, open hills of high relief/steep slopes and lowlands of low relief and, thereafter, through a deeply incised valley until it reaches the Indian Ocean approximately 85 km north of Africa's major port city of Durban (**Figure 5.1**). The mainstem Thukela's major tributaries are the Little Thukela, Mooi and Bushman's Rivers which join from the southwest, and the Klip, Sundays and Buffalo Rivers flowing in from the north.

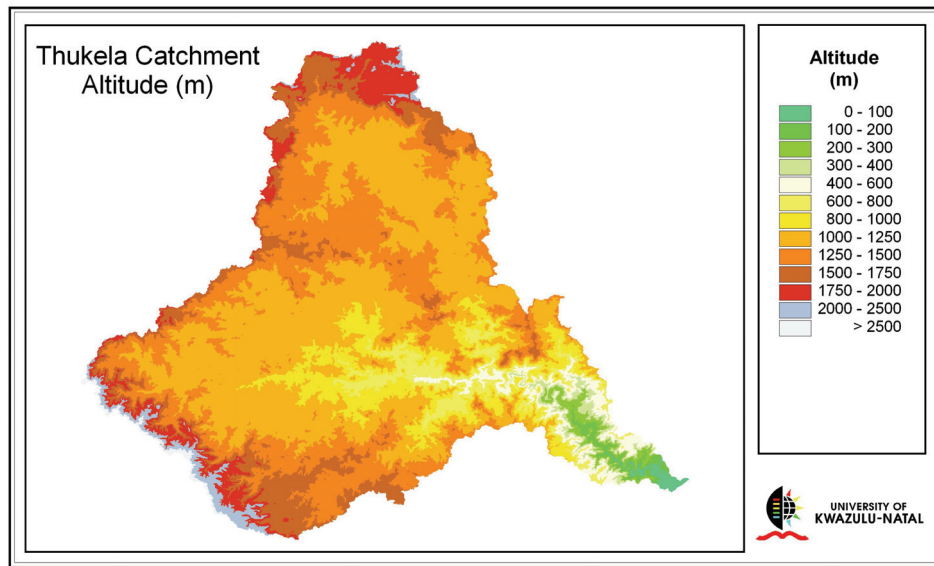


Figure 5.2 Altitude of the Thukela Catchment

Two panoramic views of the Drakensberg and its foothills are shown in **Figure 5.3** to illustrate the steep altitudinal gradients, which will affect both air temperatures and rainfall significantly, as well as resultant runoff gradients and water temperatures.

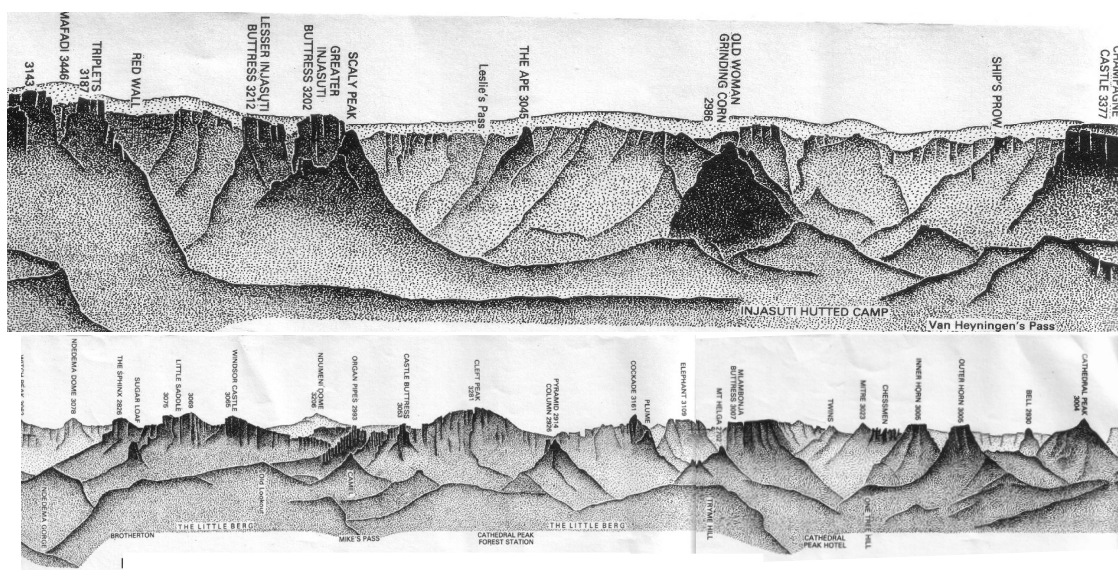


Figure 5.3 Two panoramic views of the Drakensberg (Source: KZN Wildlife)

5.3 Climate

The climate of the Thukela Catchment can best be described by ecological regions, of which seven have been identified (**Figure 5.4**; Edwards, 1967), viz. the Mountain, Highlands, Midlands Mistbelt, Interior Basins, Valleys, Coast Hinterland and Coast Lowlands regions.

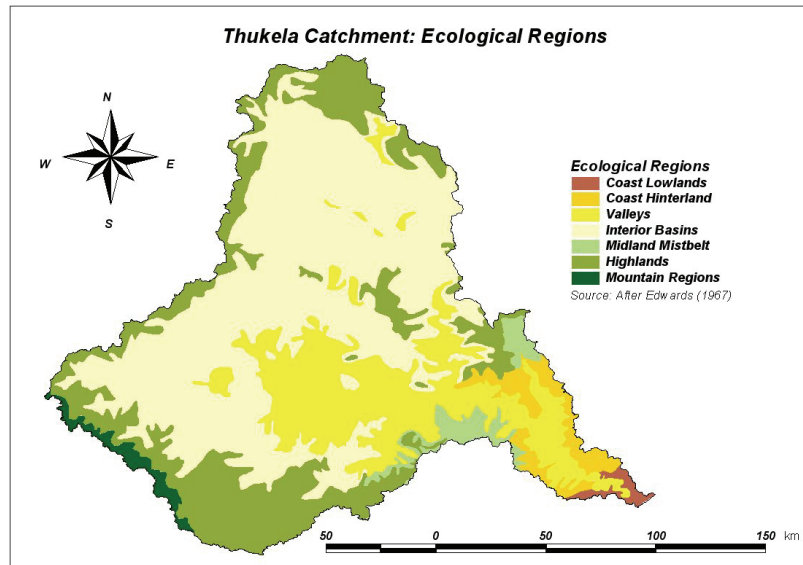


Figure 5.4 Major ecological regions in the Thukela Catchment (Edwards, 1967) as a basis for climate zone descriptions

5.3.1 Rainfall

Rainfall in the Thukela Catchment displays considerable spatial variation. Mean annual precipitation (MAP) ranges from around 2 000 mm in the Drakensberg to as low as 550 mm in the drier, lower-lying valley regions (**Figure 5.5**; Dent *et al.*, 1989; Lynch, 2004). Significant from water resources management and water temperature perspectives are the relatively high inter-annual variability of rainfall, with CVs generally in the range of 20-30% (**Tables 5.1-5.7**; Schulze, 2007).

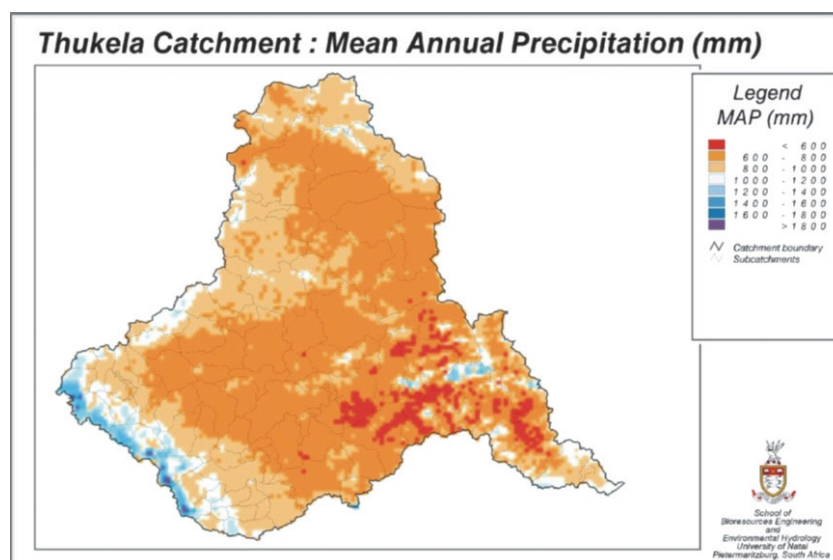


Figure 5.5 Mean annual precipitation (mm) of the Thukela Catchment (after Dent, Lynch and Schulze, 1989)

Table 5.1 Monthly and annual statistics of rainfall (mm) in the Mountain Region (after Schulze, 2007)

Statistic	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANN
Mean	200.0	184.1	176.6	69.7	23.5	9.3	10.9	35.5	57.8	96.2	144.7	187.6	1195.7
% C.V	41.3	50.4	57.4	63.3	132.5	168.1	161.6	115.6	128.5	55.1	56.6	45.2	25.8
Driest in 10	121.5	78.9	64.3	20.0	0.0	0.0	0.0	0.0	10.9	49.7	51.0	96.1	845.5
Wettest in 10	326.3	315.9	311.5	115.7	63.1	31.4	29.8	94.4	127.4	163.6	221.0	279.4	1558.2

Table 5.2 Monthly and annual statistics of rainfall (mm) in the Highlands Region (after Schulze, 2007)

Statistic	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANN
Mean	144.3	111.8	109.5	55.3	17.7	10.6	10.1	30.4	47.1	69.9	137.2	143.3	887.2
St. dev	58.4	54.0	53.6	31.9	22.5	22.0	13.6	30.5	56.9	35.5	63.5	60.4	176.2
Driest in 10	74.9	40.5	52.7	15.7	0.0	0.0	0.0	0.0	8.9	29.0	61.7	67.2	667.2
Wettest in 10	221.1	191.8	173.1	90.0	56.3	28.3	34.2	83.7	106.6	121.8	232.3	208.0	1117.1

Table 5.3 Monthly and annual statistics of rainfall (mm) in the Midlands Mistbelt Region (after Schulze, 2007)

Statistic	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANN
Mean	112.2	86.8	66.7	37.5	13.2	8.5	9.5	16.6	39.3	65.5	86.3	103.9	646.0
% C.V	55.0	63.5	54.9	69.1	145.4	171.7	194.6	119.1	171.8	56.4	47.5	73.3	20.7
Driest in 10	50.4	31.0	16.3	6.5	0.0	0.0	0.0	0.0	0.0	18.2	40.2	51.4	498.3
Wettest in 10	204.8	157.9	108.9	72.6	39.9	32.0	28.7	48.0	58.8	114.6	131.2	155.7	815.3

Table 5.4 Monthly and annual statistics of rainfall (mm) in the Interior Basins Region (after Schulze, 2007)

Statistic	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANN
Mean	137.5	107.4	85.1	39.7	16.1	6.6	7.9	19.0	40.3	86.6	113.5	135.6	795.3
% C.V	52.3	58.9	53.0	70.9	125.2	149.5	203.9	107.1	114.0	61.7	47.3	56.3	20.4
Driest in 10	56.7	25.1	31.1	0.3	0.0	0.0	0.0	0.0	1.1	27.2	50.7	53.8	587.0
Wettest in 10	226.6	198.7	148.0	87.1	43.5	23.2	21.0	48.9	79.8	160.5	189.2	236.7	991.6

Table 5.5 Monthly and annual statistics of rainfall (mm) in the Valley Region (after Schulze, 2007)

Statistic	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANN
Mean	131.1	111.7	86.6	39.1	11.7	5.4	4.5	15.5	42.0	65.2	83.2	121.7	717.6
% C.V	54.4	57.6	60.2	63.4	135.9	166.4	171.3	121.2	137.5	71.9	58.1	51.8	21.5
Driest in 10	52.0	32.2	18.9	12.2	0.0	0.0	0.0	0.0	0.0	16.4	34.3	47.7	538.7
Wettest in 10	234.6	196.5	156.2	69.3	31.1	19.9	19.3	43.9	91.2	131.3	140.4	212.9	886.6

Table 5.6 Monthly and annual statistics of rainfall (mm) in the Coast Hinterland Region (after Schulze, 2007)

Statistic	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANN
Mean	132.8	119.8	99.1	54.7	38.3	21.6	24.4	35.7	87.0	102.2	117.6	122.0	955.1
% C.V	48.1	74.5	66.9	75.9	119.7	114.9	136.5	90.2	139.8	47.1	50.2	54.7	24.4
Driest in 10	59.7	41.0	29.1	14.2	1.9	1.7	0.9	6.3	15.2	43.7	61.4	51.3	706.2
Wettest in 10	226.6	244.3	188.5	104.3	90.5	55.5	58.5	82.8	203.5	163.1	176.3	185.3	1229.2

Table 5.7 Monthly and annual statistics of rainfall (mm) in the Coast Lowlands Region (after Schulze, 2007)

Statistic	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANN
Mean	135.8	121.6	101.9	60.7	56.3	33.8	32.2	41.0	81.7	107.7	118.0	91.6	982.4
% C.V	60.1	69.4	71.0	80.3	156.2	110.3	118.6	81.5	118.2	55.5	57.1	49.2	26.9
Driest in 10	46.0	33.4	16.8	6.2	0.5	0.1	3.4	4.1	16.6	39.6	67.1	42.4	686.5
Wettest in 10	216.3	218.6	174.7	144.5	129.2	96.4	79.7	97.9	167.7	186.8	172.7	155.1	1363.2

The driest year in 10 records only about 60% of MAP. Equally as important as the rainfall's high monthly variability is its strong concentration in the summer months. Most of the rainfall (> 80%) is received during the wet summer season between October and March (**Tables 5.1-5.7**; Schulze, 2007). The coastal region is an exception because it has relatively wet winters during which about 30% of the annual rainfall is received. In relation to the other months, January is the wettest month with the rainfall ranging between 100 and 300 mm (mostly 120-150 mm). June and July are the driest months, with means of those respective months' rainfalls over most of the Catchment being about 10 mm (**Tables 5.1-5.7**).

5.3.2 Temperatures

Mid-summer (January) monthly means of daily maximum temperatures generally range from about 24°C to 28°C (**Table 5.8**), with the highest values occurring in the Valley Region, while in the high Drakensberg mountains they seldom exceed 20°C (Schulze, 1997). The Drakensberg mountains also record the lowest monthly means of daily minimum temperatures, with sub-zero means of minima not uncommon in July (Schulze, 2007). Unlike the cold Mountain Region, the coastal areas are fairly mild during mid-winter with means of daily minimum temperatures averaging about 10°C in July.

Table 5.8 Monthly means of daily maximum and minimum temperatures (°C) for selected subcatchments representing major ecological regions (Source: Schulze, 2007)

Region	Variable	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Mountain Region	Min	11.8	11.6	10.2	7.1	3.8	0.8	0.9	2.8	5.6	7.6	9.3	10.8
	Max	24.3	23.5	22.5	20.3	17.7	15.6	15.8	17.6	20.7	21.4	22.1	23.9
Highlands	Min	12.6	12.5	10.9	7.8	4.1	0.7	0.9	3.2	6.2	8.2	9.9	11.7
	Max	24.7	23.9	23.3	21.1	18.6	16.6	16.8	18.6	21.2	21.5	22.2	24.1
Midland Mistbelt	Min	15.1	15.0	14.0	11.2	7.9	4.8	4.9	6.9	9.3	11.0	12.6	14.2
	Max	26.0	26.0	25.2	23.4	21.3	19.1	19.4	20.9	22.6	23.4	24.0	25.9
Interior Basins	Min	14.0	13.7	12.4	9.4	5.7	2.5	2.5	4.8	8.0	10.0	11.6	13.2
	Max	26.1	25.7	25.1	23.1	21.1	18.7	19.0	20.9	23.1	23.7	24.4	25.9
Valley	Min	15.5	15.4	14.1	10.7	6.6	3.2	3.2	5.6	8.9	11.2	13.0	14.6
	Max	28.3	28.0	27.1	24.9	22.7	20.3	20.7	22.5	24.5	25.4	26.5	28.1
Coast Hinterland	Min	18.3	18.4	17.5	15.1	12.0	9.0	8.9	10.6	12.9	14.3	15.8	17.4
	Max	27.3	27.4	26.8	25.3	23.8	21.9	21.9	22.7	23.5	24.2	25.0	26.8
Coast Lowlands	Min	19.7	19.7	18.8	16.2	13.1	10.2	10.0	11.7	14.0	15.6	17.0	18.7
	Max	27.9	27.9	27.4	25.9	24.5	22.9	22.6	23.0	23.9	24.6	25.4	27.2

5.3.3 Potential evaporation

Atmospheric moisture demand, expressed through potential evaporation (E_p), is an important modulator in the conversion of rainfall to runoff within the Thukela Catchment. It varies widely, both spatially and temporally, with the average annual E_p , when using the A-pan as a reference, being between 1600 and 1900 mm per annum (Schulze, 1997). Highest monthly means of E_p (175-220 mm) coincide with high means of maximum temperatures in January and similarly the lowest values,

still around 90 mm per month, occur in June (Schulze, 1997). The monthly means of E_p in the major ecological regions in the Catchment are summarised in **Table 5.9**. The ratio of mean annual rainfall to mean annual E_p , which can be used as an indicator of aridity levels, shows that about 88% of the Thukela Catchment may be classified as semi-arid. This implies that despite the rainfall *per se* not necessarily being low everywhere, it is not sufficient to satisfy the atmospheric moisture demand.

Table 5.9 Monthly means of A-pan equivalent reference potential evaporation (mm) for selected subcatchments representing major ecological regions in the Thukela Catchment (after Schulze, 1997)

Region	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
Mountain Region	175.4	148.5	134.9	117.3	96.1	89.0	99.3	135.0	155.2	156.4	157.3	181.5	1645.9
Highlands	174.5	148.8	141.7	121.1	103.3	91.6	102.8	133.8	153.2	155.8	157.1	178.6	1662.3
Midland Mistbelt	186.4	160.2	152.3	124.9	110.3	96.4	104.8	134.6	153.8	165.1	167.3	188.0	1744.1
Interior Basins	194.7	164.0	155.9	125.8	107.7	93.5	104.3	140.3	163.1	174.8	177.9	202.0	1804.0
Valley	206.1	176.1	163.8	126.8	106.5	92.6	102.1	135.7	163.7	180.6	187.6	209.5	1851.1
Coast Hinterland	186.3	162.4	160.4	127.7	110.3	91.7	102.1	125.2	139.2	165.5	166.3	187.6	1724.7
Coast Lowlands	188.7	164.6	164.3	129.7	110.4	88.1	101.4	122.0	134.0	165.5	168.5	190.6	1727.8

5.4 Soils

Soils are a major regulator of hydrological responses in that through/across the soil infiltration, drainage, evapotranspiration and runoff processes occur. In South Africa soils are mapped by so-called “land types”, each with a marked degree of a uniformity with respect to broad soil patterns, terrain form and climate (Land Type Survey Staff, 1986). Of the nine broad categories of soil land types identified in South Africa, seven are found in the Thukela Catchment, these being predominantly deep and freely drained apedal soils (23.1%) and skeletal, often poorly drained soils mainly of the Glenrosa and/or Mispah soil forms (37.4%). The spatial distributions of selected hydrologically relevant characteristics of the soils found in the Thukela are shown in **Figure 5.6** (Schulze and Horan, 2007). Soil depths vary from < 0.3 m to > 1.0 m, while plant available water, which varies by texture, ranges < 0.04 m/m to over 1.00 m/m and the soils’ erodibility factors are from as low as 0.13 to being > 0.70.

5.5 Land Cover

Through above-ground biomass, surface litter/mulch and below-ground rooting characteristics land cover affects soil moisture and hence runoff processes as well as sediment yield production. In this study on water temperature (dependent *inter alia* on runoff), all indices are computed assuming a baseline natural vegetation, and not present land uses. The vegetation classification most commonly used in South African hydrology as an indicator of baseline land cover is that by Acocks (1988), who delineated South Africa, Lesotho and Swaziland into 70 so-called “Veld Types”. **Figure 5.7** shows the spatial distribution of the 14 Veld Types found within the Thukela Catchment. The Catchment is dominated by Valley Bushveld, Southern Tall Grassveld, Natal Sourveld and the Highveld Sourveld and Döhne Sourveld. Other important Veld Types are the Ngongoni Veld and the Coastal Forest and Thornveld found in the lower coastal end of the Catchment.

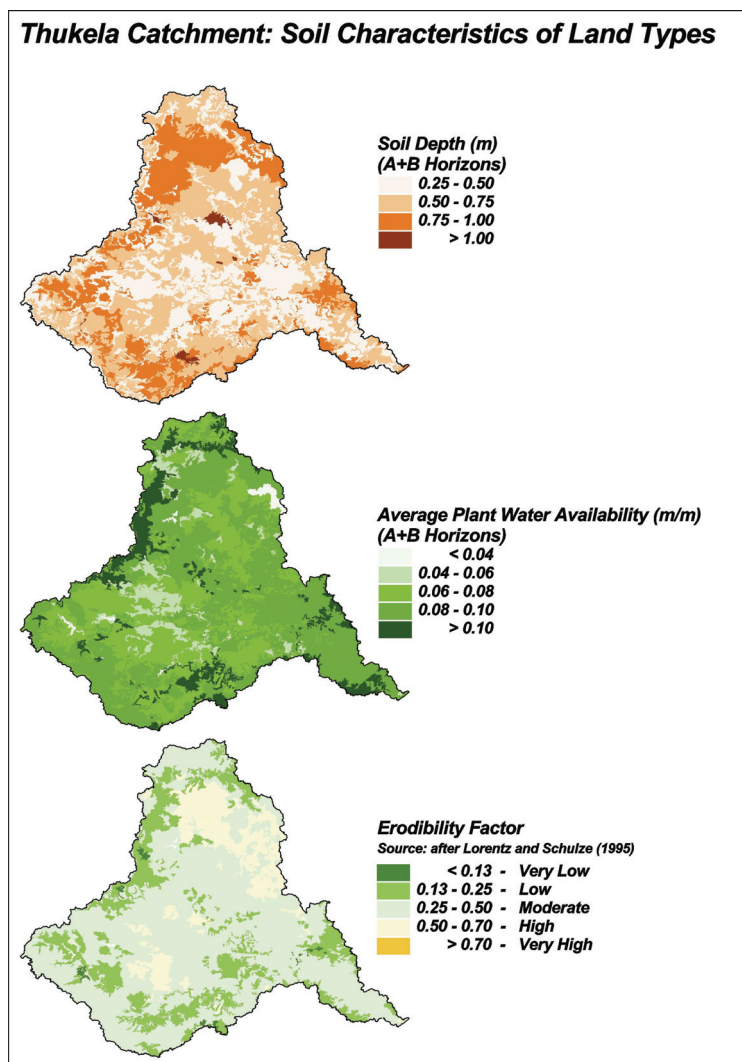


Figure 5.6 Distribution of selected soil characteristics in the Thukela Catchment (after Schulze and Horan, 2007)

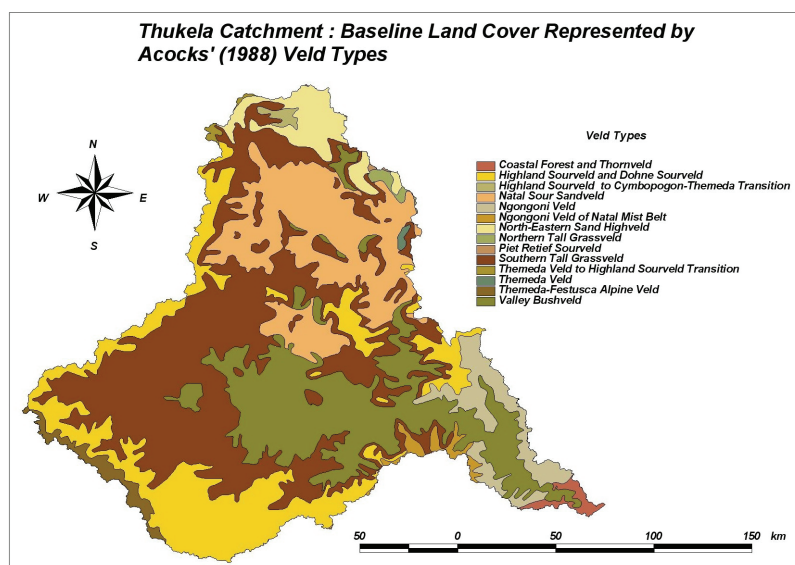


Figure 5.7 Baseline land cover in the Thukela Catchment as represented by Acocks' (1988) Veld Types

5.6 Hydrology

For hydrological analyses the Thukela Catchment was sub-delineated into 258 Quinary level subcatchments (cf. **Chapter 6**). For the period 1971-1990 the mean annual baseline runoff (made up of stormflows and baseflows) per individual subcatchment varies from $< 1000 \text{ m}^3$ to $> 250\,000 \text{ m}^3$ (i.e.: $< 25 \text{ mm}$ equivalent runoff per annum in the drier valley areas, to $> 250 \text{ mm}$ in the high rainfall areas of the west; **Figure 5.8**, top). Accumulated flows show a much more even flow distribution and the dominance of the mainstem Thukela and its major tributaries is very much in evidence (**Figure 5.8**, bottom). The coefficient of variation of annual streamflows ranges from $< 40\%$ to around 200% (Schulze *et al.*, 2005), with the variability of accumulated streamflows displaying much more muted patterns than those of individual subcatchments (Schulze *et al.*, 2005). Water quality of the Thukela system, reflected by the patterns of Total Dissolved Solids loadings, has been shown to be largely dependent on the location of coal mines within the Catchment (Chersa *et al.*, 2005).

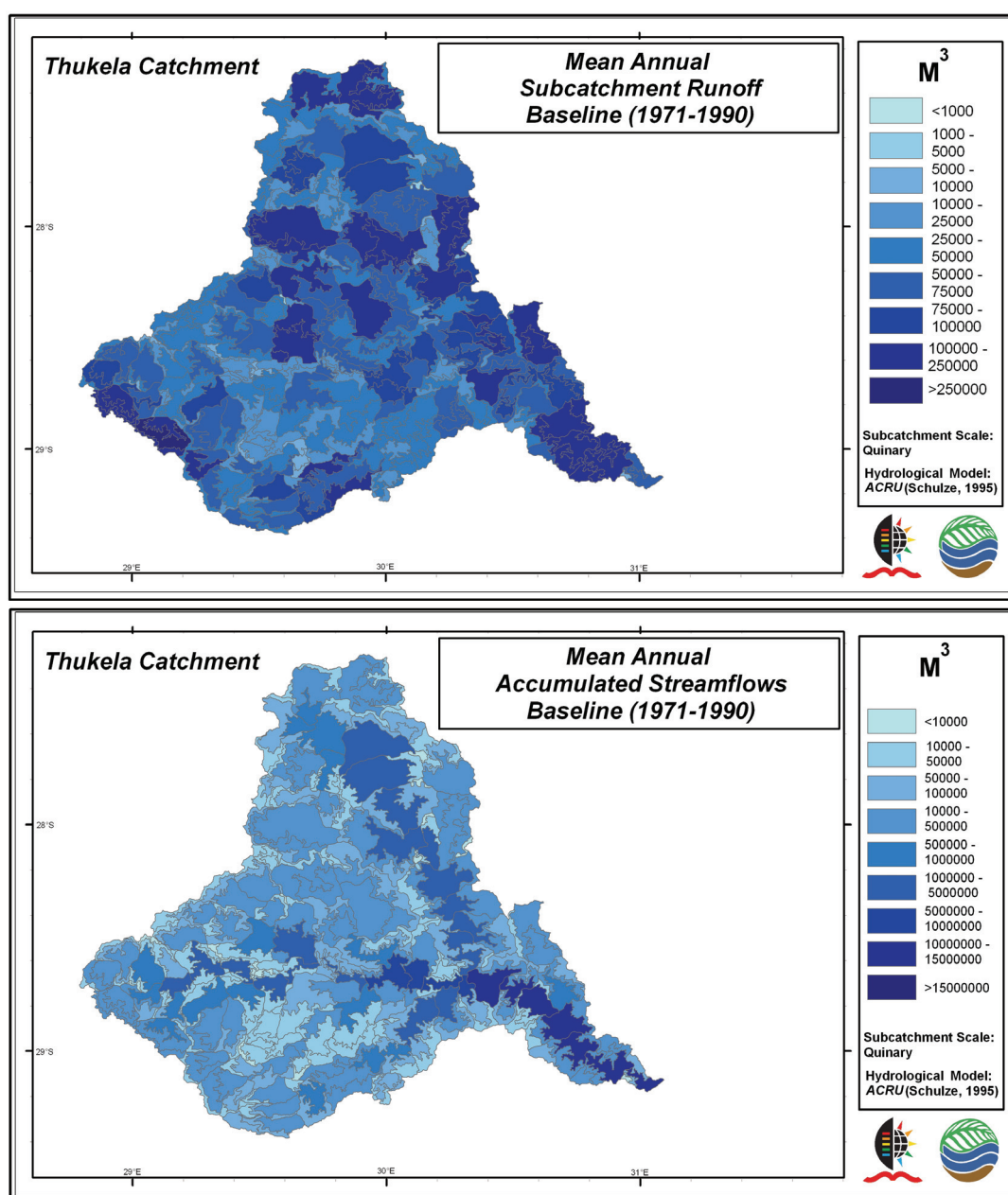


Figure 5.8 Distributions of mean annual streamflows for individual subcatchments and accumulated flows (This report)

5.7 Socio-Economic Profile

Although the present water temperature study in the Thukela Catchment is essentially a biophysical one, some socio-economic background is nevertheless provided in order to place the research in a broader perspective of vulnerabilities under conditions of climate change. Unless otherwise referenced, this information was provided by Dlamini (2005) and was based on data from the National Population Census databases (StatsSA, 1996; 2001) and a water poverty study.

5.7.1 Present settlements and demography

The total population of the Catchment given by the 2001 Census is ~ 2 068 000, i.e. an average population density of 71 persons per km². A majority of the population (56.45%) resides in historically tribal areas, while about a quarter of the total population (25.77%) is in urban areas. The spatial patterns of population density for both the 1996 and 2001 Population Census' suggest that the people in rural areas of the Thukela Catchment live in dwellings that are dispersed over larger areas compared to those who live in nucleated urban areas.

5.7.2 Economic wellbeing

Overall, the Thukela Catchment is relatively poor, with low skills levels, limited economic activity and low income levels prevailing over large areas. More than 20% of the adult population never had formal education and a further > 40% only primary schooling, while only 23% are in formal employment. The average economic dependency ratio (defined as the total of the 0-14 and the 65+ age groups as a proportion of the overall numbers employed) is quite high at about 3.7, which implies that each employed person supports about 4 dependants. Average per capita income is R5 400 per annum, which is well below the national average of R12 900 (Wilson, 2001). The spatial patterns of socio-economic disadvantage in the Catchment are illustrated in **Figure 5.9** by a poverty index, a composite measure that takes into account the levels of literacy, essential service provision and economic dependency.

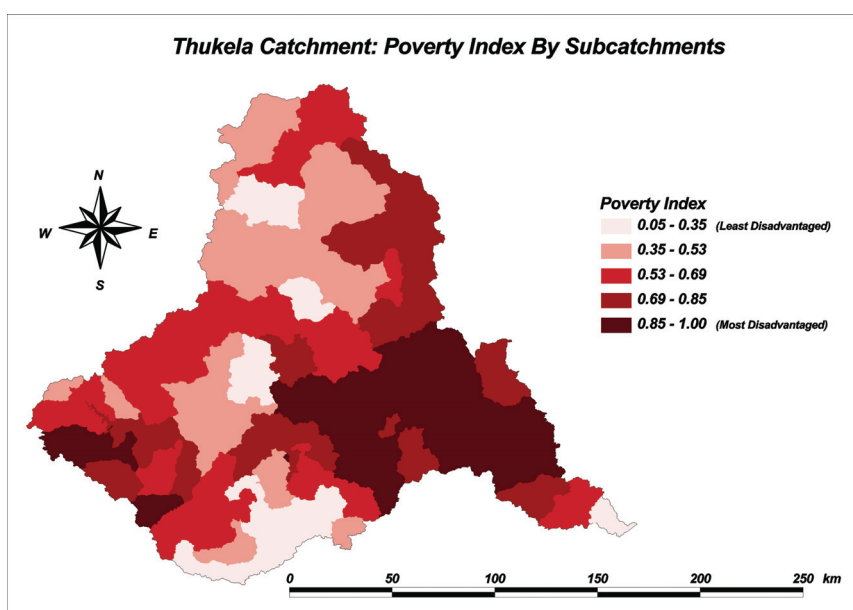


Figure 5.9 An overall index of poverty, per subcatchment, in the Thukela Catchment (after Wilson, 2001)

5.7.3 Household services

The levels of household services provision in the Thukela Catchment vary considerably, but are generally poor. In 2001 more than 100 000 households (24%) still collected water directly from dams, pools, stagnant water, springs, rivers and streams and, in total, 48% of households were still served with unprotected water and were thus susceptible to water-borne diseases, which is likely to be exacerbated by projected higher water temperatures with climate change. This susceptibility remains a real concern when viewed in light of the > 100 000 households without any form of sanitation, or the > 80 000 that in 2001 still did not have access to organised refuse disposal facilities (cf. **Figure 5.10**).

The spatial patterns of household services (**Figure 5.10**) in the Catchment indicate that the levels of delivery vary with the types of settlements, with subcatchments in rural areas tending to have the largest proportions of households using unprotected water sources, without proper sanitation, without electricity connections, or without reachable telephone facilities. On the other hand, the access levels in urban areas are relatively high (often more than 60%), irrespective of the type of service. Fieldwork by Dlamini (2005) in a water poverty study furthermore noted that many household units in the rural communities are scattered along ridge lines. Associated with the poor access to services in the rural areas is the limited infrastructural development. The rugged terrain of large parts of the Catchment and the tendency of the settlements to be scattered along ridge line make infrastructural development both an engineering challenge and a prohibitively expensive undertaking.

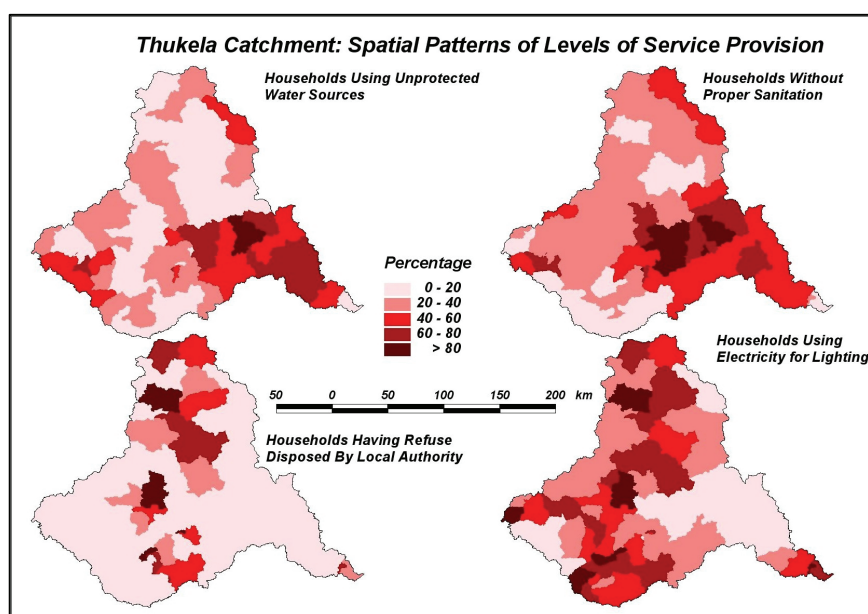


Figure 5.10 Spatial patterns, per subcatchment, of the provision of selected services in the Thukela Catchment (Dlamini, 2005; Source: StatsSA, 2001)

5.8 Concluding Thoughts

The Thukela Catchment has been shown to be highly diverse - physiographically, climatically and socio-economically. The distribution of water temperature, and the prospect of changes in water temperature with climate change are, therefore, likely to be equally diverse, if not more so, both spatially as well as temporally, with possibly significant consequences on the aquatic environment.

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CHAPTER 6 METHODS 1: DELINEATION OF SOUTH AFRICA, LESOTHO AND SWAZILAND INTO QUINARY CATCHMENTS

R.E. Schulze and M.J.C. Horan

6.1 On Sensitivities of Runoff to Climatic and Catchment Variables

Of the wide range of variables which influence hydrological responses, it has been shown many times that rainfall, reference potential evaporation and certain soil characteristics are arguably the ones to which the generation of the most important components of runoff, viz. stormflow and baseflow, as well as irrigation water demand are most sensitive. The strong curvilinear sensitivity of runoff to rainfall, from individual events to long term seasonal responses, and for local to regional scales, has been widely documented for southern Africa, for example by Schulze (1979; 1983), Dent *et al.* (1989) and Lynch (2004), and in each case the patterns of rainfall have been found to be strongly related to altitude *per se*, as well as to the rate of change in altitude. Similarly, potential evaporation, which is often derived implicitly or explicitly from temperature parameters, has a strong relationship with altitude (e.g. Schulze, 1997; 2007), while stormflow generation is highly sensitive to the critical depth of near-surface soil and the magnitude and frequency of recharge of soil water into the groundwater zone from which baseflows are generated, is highly dependent on the total soil profile thickness (Schulze, 1995).

6.2 Current Level of Spatial Disaggregation used in South African Hydrological Studies

For operational decision making, South Africa has been delineated into 22 Primary Catchments, each of which has been sub-divided into interlinked Secondary, thereafter into Tertiary and, at the fourth level, into hydrologically cascading Quaternary Catchments (QCs), of which 1 946 make up the contiguous area of the RSA, Lesotho and Swaziland (**Figure 6.1**). When modelling hydrological responses, each QC has, to date, been assigned a single set of catchment representative rainfall and reference potential evaporation time series values while again one set of soils attributes, usually area-averaged, has been assigned for the entire QC.

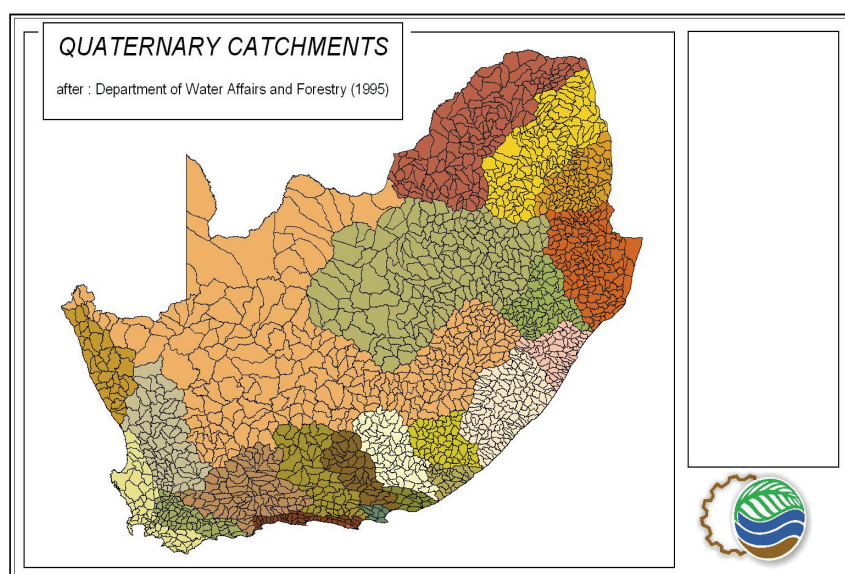


Figure 6.1 Primary and Quaternary catchments covering South Africa, Lesotho and Swaziland (After DWAF, 2000)

6.3 The Need for Further Spatial Disaggregation in Southern Africa for Hydrological Purposes

However, within many Quaternary Catchments considerable physiographic heterogeneity exists. For example, statistical analysis has shown that intra-QC variability of one arc minute ($\sim 1.7 \times 1.7$ km) gridded altitude and rainfall values is high enough for approximately 1000 of the 1946 QCs to require subdivision into smaller, more homogeneous response units on the grounds of natural hydrological variability alone (Schulze, 2004). This is illustrated in **Figure 6.2**, in which differences in gridded altitude values between the 90th and 10th percentiles are shown for each QC, depicting the many QCs with altitudinal ranges in excess of 400 m which may need to be discretised further when based solely on the influence which altitude has on drivers of runoff such as rainfall and on buffers on runoff such as soils properties and potential evaporation (Schulze, 2004).

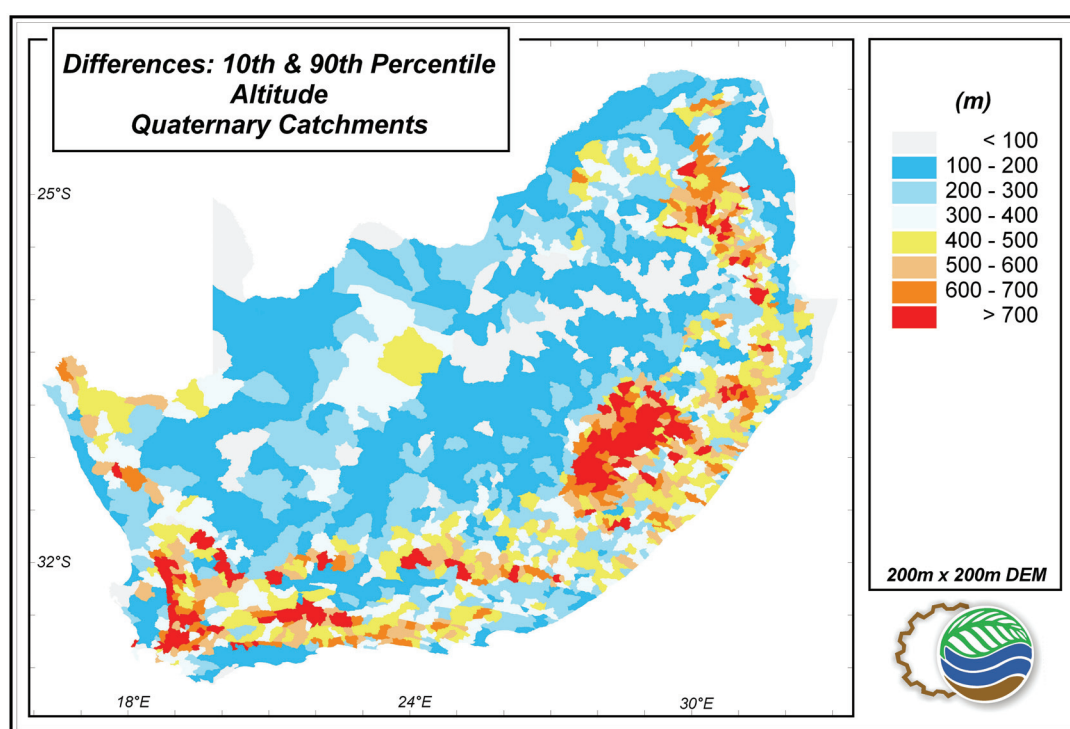


Figure 6.2 Differences between the 10th and 90th percentile values of one arc minute gridded altitudes per Quaternary Catchment (After Schulze, 2004)

6.4 Methods of Disaggregating Catchments into Relatively Homogeneous Hydrological Response Units

There are many methods of discretising catchments into relatively homogeneous units for modelling purposes (cf. Krause, 2001; Schulze, 2005), including

- *raster discretisation* into fixed, equal sided cells to be modelled individually and then linked - a method which assures high parameter homogeneity of individual cells;
- *delineation into subcatchments by topographic watershed boundaries*, such as subdivision of QCs into smaller units according to natural hydrological criteria (e.g. dominant land uses, soils, physiography, climate) or water resources management criteria (e.g. gauging stations, IFR sites, dam sites, abstraction points; e.g. **Figure 6.3**); these are then hydrologically interlinked, with outflows of upstream becoming inflows into downstream subcatchments; however, each

subcatchment may still display relatively high intra-catchment heterogeneity of relevant parameters and dominant processes may, therefore, be integrated and still misrepresented hydrologically;

- *land use classified subcatchments*, where each catchment is divided into pre-selected land use classes (each with assumed homogeneous hydrological responses) by area, for rapid application when impacts of present or anticipated future land use scenarios are evaluated by the model (Figure 6.3);
- *hydrologically homogeneous response units*, created by GIS overlays of relevant hydrological variables (e.g. slope, soils, land use) and where subdivision of these highly homogeneous units can be effected at different spatial resolutions of basic data according to their local criticality, but where the spatial scattering of individual units are not connected in any hydrologically logical manner; and
- *discretisation by similar runoff generation processes* which delineate, for example, areas dominated by (say) Hortonian overland flow, saturated overland flow, interflow, or preferential recharge zones; alternatively, using toposequentially derived terrain units in which water cascades downslope (at, near or below the surface) from crest to scarp (if present) to midslope, the footslope zone to the riparian (or variable source area) zone.

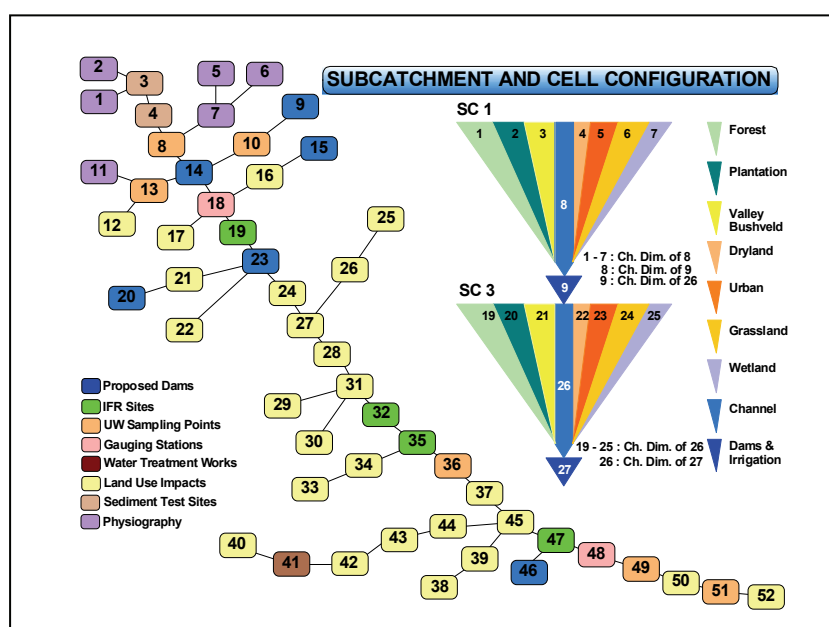


Figure 6.3 An example from the Mkomazi catchment of subcatchment discretisation by watershed boundaries and with further sub-delineation by land use classification (After Taylor *et al.*, 2001)

6.5 Approach Taken for a Southern Africa Scale Sub-Delineation of Quaternary Catchments into Quinary Catchments of More Homogeneous Hydrological Response

None of the above means of disaggregating fourth level Quaternary Catchments into hydrologically more homogeneous response areas was deemed suitable as a workable, consistent and altitude derived methodology for southern Africa.

In order to achieve a consistent methodology of sub-delineating fourth level Quaternary Catchments into fifth level Quinary Catchments according to altitude criteria, each Quaternary was therefore subdivided consistently into three Quinaries, i.e. an Upper, Middle and Lower Quinary, of unequal

area but of similar topography, by applying the Jenks' optimisation procedures available within the ArcGIS software suite, and which are based on a sub-delineation according to "natural breaks" in altitude. The individually determined natural breaks between adjacent Quaternaries were then edge-matched by smoothing. The entire concept is illustrated in **Figure 6.4** for two Quaternary Catchments, with altitude shown in the left hand map, the three-fold sub-delineation by natural breaks of altitude by Jenks' procedures in the middle map and the flowpaths of runoff from the Upper to Middle and Middle to Lower Quinary in the right hand map.

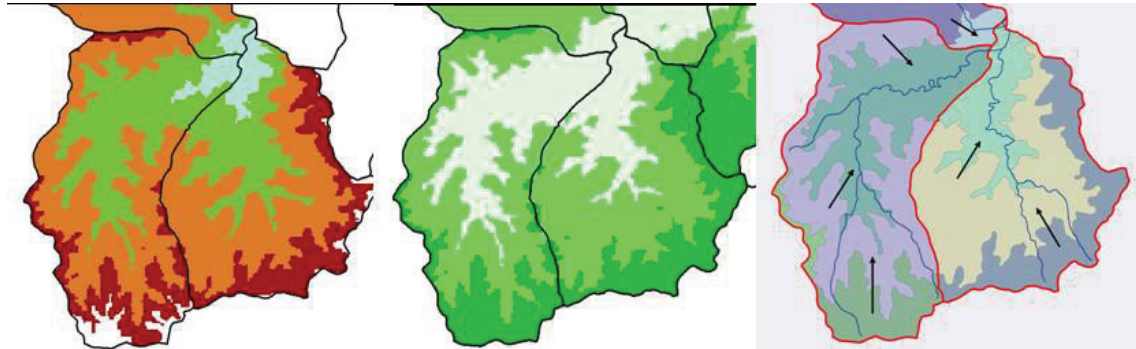


Figure 6.4 Sub-delineation of Quaternary Catchments from altitude (left) into three Quinaries by natural breaks (middle) with flow paths of water (right)

Two points need to be stressed in regard to the sub-delineation into Quinaries:

- First, because the three Quinaries within each QC are delineated by natural altitude breaks, a specific Quinary may be made up of one or more discrete spatial units, i.e. polygons, as in the example of the Upper Quinary in **Figure 6.4** (middle). These polygons are nevertheless conceptualised as **one single spatial entity** for purposes of hydrological simulations, with all runoff generated from those polygons flowing into the next downstream Quinary.
- Secondly, the outflow of the Lower Quinary of a QC (irrespective of whether that QC is an "external" or "internal" Quaternary), does **not** enter the Upper Quinary of the next downstream Quaternary Catchment, because that Upper Quinary may be at a higher altitude than the Lower Quinary of the upstream Quaternary. Therefore, the outflow of the Lower Quinary has been configured to rather enter the downstream Quaternary at its exit. A schematic of the flowpath configuration between Quinaries and Quaternaries, taken from the Upper Thukela Catchment, is given in **Figure 6.5**.

6.6 Outcomes of the Delineation into Quinary Catchments

The sub-delineation of Quaternary into Quinary Catchments has four primary outcomes:

- The first is that the RSA, Lesotho and Swaziland have now been delineated into 5 838 hydrologically interlinked and cascading Quinaries (**Figure 6.6**) from exterior through interior subcatchments with water eventually flowing out to sea, or into neighbouring countries (such as Mozambique), or into international border rivers (such as the Limpopo or the Orange).
- The second is that the Quinary Catchments are deemed to be more homogeneous than the Quaternaries in their altitudinal range. This is illustrated clearly when comparing the much lower altitudinal ranges of the Quinaries shown in **Figure 6.7** with the much higher ones of the Quaternaries in **Figure 6.2**.

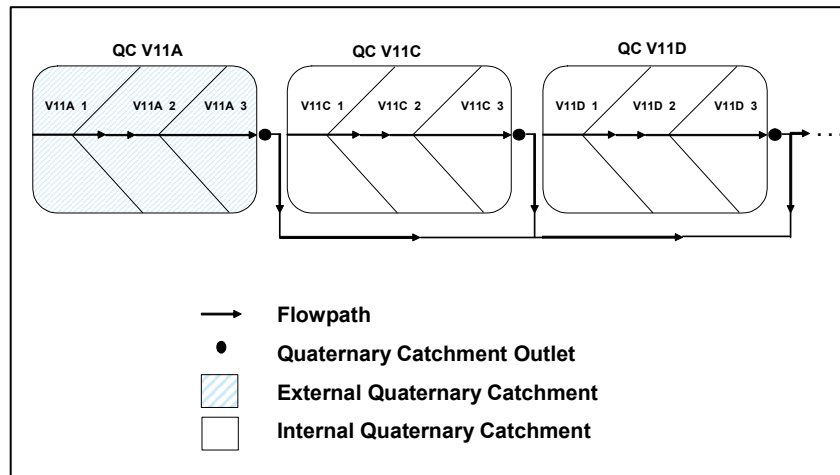


Figure 6.5 Example of flowpaths between Quinary and Quaternary Catchments in the Upper Thukela Catchment (Schulze and Horan, 2007)



Figure 6.6 Delineation of the RSA, Lesotho and Swaziland into 5 838 hydrologically interlinked and cascading Quinary Catchments

- The third is that, especially in higher altitude runoff-producing Quaternary Catchments, the differences between hydrologically relevant attributes of the three Quinaries within a Quaternary can be highly significant. This is illustrated in **Table 6.1**, in which differences in mean annual precipitation (to which runoff responds curvilinearly), slope (a variable in peak discharge estimation), reference potential evaporation (a determinant of soil moisture) and soil profile thickness (which is a control variable of recharge to groundwater) are markedly different between Quinaries, and would therefore yield markedly different hydrological responses than the Quaternary which they make up.

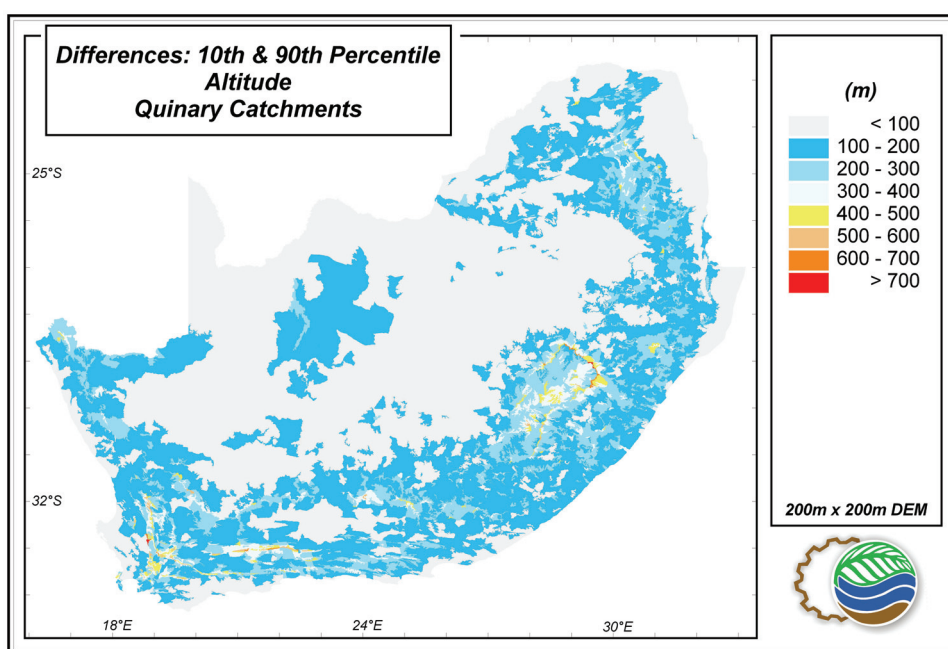


Figure 6.7 Differences between the 10th and 90th percentile values of one arc minute gridded altitudes per Quinary Catchment

Table 6.1 Differences between Upper, Middle and Lower Quinary Catchment characteristics within nine Quaternary Catchments in the Upper Thukela area, KwaZulu-Natal (Schulze and Horan, 2007)

Quaternary Catchment	Quinary Number	Flows Into	Area (km ²)	MAP (mm)	Altitude (m)	Slope (%)	T _{max} (Jan)	T _{min} (Jul)	A-pan (Jan)	Soil Thickness (m)
V11A	1	2	20.47	1290	2790	37.9	17.7	-0.7	124	.40
	2	3	73.44	1156	2009	28.2	23.2	1.2	176	.53
	3	9	113.09	1006	1508	15.8	26.3	0.8	208	.69
V11B	4	5	49.51	1484	2724	49.0	14.6	-3.9	109	.37
	5	6	91.59	1430	2058	31.6	21.9	0.7	160	.62
	6	15	119.91	1125	1625	21.1	25.1	1.2	188	.66
V11C	7	8	38.06	980	1767	24.8	24.5	1.3	188	.48
	8	9	21.45	1026	1504	17.4	25.6	1.6	197	.61
	9	12	126.25	905	1294	6.6	27.8	0.5	223	.83
V11D	10	11	7.14	1020	1600	22.5	25.0	3.5	194	.57
	11	12	25.83	998	1396	17.3	26.6	2.3	205	.71
	12	27	190.32	816	1243	4.3	28.0	1.8	217	.77
V11E	13	14	52.55	1176	2019	18.5	22.5	1.8	168	.73
	14	15	37.12	1213	1580	22.4	25.8	1.5	195	.62
	15	27	77.61	1023	1286	10.2	27.3	1.6	209	.73
V11F	16	17	9.88	943	1533	15.9	25.4	1.6	198	.49
	17	18	52.94	795	1308	7.8	27.3	1.8	210	.73
	18	27	98.01	723	1200	2.9	28.1	2.1	217	.83
V11G	19	20	21.89	1668	2922	52.1	16.1	-2.6	115	.40
	20	21	169.30	1452	1998	26.3	22.0	0.5	160	.74
	21	24	90.87	1196	1558	21.5	25.0	1.3	185	.63
V11H	22	23	9.59	1288	1878	32.9	23.0	2.3	172	.59
	23	24	21.35	1216	1488	19.5	25.6	2.2	190	.69
	24	27	79.80	885	1281	9.1	27.3	1.9	205	.73
V11J	25	26	15.47	968	1461	15.9	26.5	2.3	201	.73
	26	27	18.33	877	1289	13.4	27.2	2.4	208	.65
	27	Exit	95.69	742	1174	3.8	28.2	2.1	216	.84

- The fourth is that certain land uses within a Quaternary Catchment are often dominant within specific Quinaries of that QC. For example, in **Figure 6.8** it may be seen that unimproved grassland in a set of Quaternaries in the Eastern Cape Drakensberg tend to be the dominant land use in the Upper and Middle, but not generally in the Lower, Quinaries, while in **Figure 6.9** it is seen that degraded areas in the same QCs are a feature of the Lower rather than the other two Quinaries (Schulze and Horan, 2007).

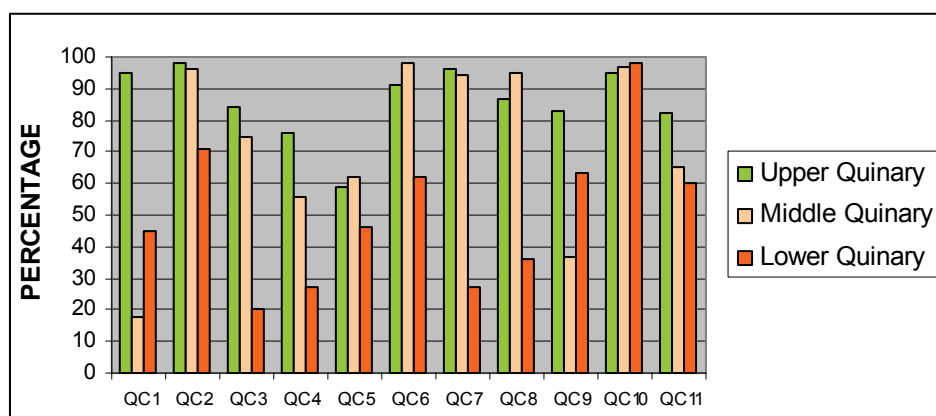


Figure 6.8 Examples of land use differences between Quinaries 1: Dominance of unimproved grassland as a percentage of all land use categories in the Upper and Middle Quinaries compared with the Lower Quinary in a set of Quaternaries in the Eastern Cape Drakensberg (Schulze and Horan, 2007)

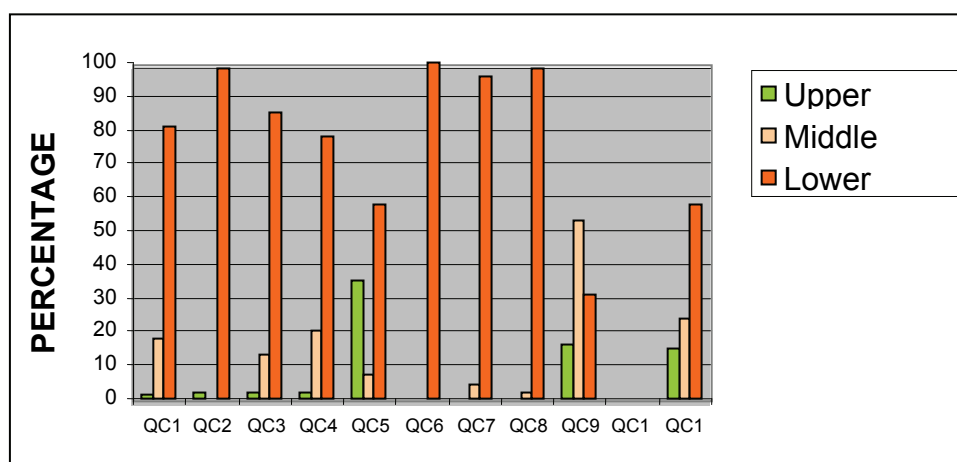


Figure 6.9 Examples of land use differences between Quinaries 2: Dominance of degraded areas as a percentage of all land use categories in the Lower Quinaries in a set of Quaternaries in the Eastern Cape Drakensberg (Schulze and Horan, 2007)

6.7 Conclusions

In this chapter it was shown that many fourth level Quaternary Catchments in southern Africa are physiographically too diverse for hydrological responses from them to be considered homogeneous. A three-fold altitude break based sub-delineation into fifth level Quinary Catchment has been shown to introduce a far greater measure of hydrological homogeneity for detailed assessments of hydrological responses. Local homogeneity in regard to rainfall, temperatures, slope, soil attributes and typical land uses is important also in ecological flow responses (cf. **Chapter 13**) as well as in

adaptation strategies to climate change, which in implementation will depend very much on local landscape characteristics.

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CHAPTER 7 METHODS 2: DEVELOPMENT OF THE SOUTHERN AFRICAN QUINARY CATCHMENTS DATABASE

R.E. Schulze, M.J.C. Horan, R.P. Kunz, T.G. Lumsden and D.M. Knoesen

7.1 From a Quinary Catchments Delineation to a Quinary Catchments Database for Southern Africa

For a number of years now many assessments of hydrological and agricultural responses over southern Africa have been made using the Southern African Quaternary Catchments Database, or QDB (e.g. Schulze and Perks, 2000; Gush *et al.*, 2002; Schulze *et al.*, 2005a). This QDB has been described in detail by Schulze *et al.* (2005b), and the daily time step conceptual-physical and multi-purpose *ACRU* model (Schulze, 1995 and updates) has been linked to it. The QDB had its origins in the late 1980s and since then it has been revised, reconstructed and expanded upon in a series of iterations (e.g. Dent *et al.*, 1989; Meier, 1997; Perks *et al.*, 2000; Hallows *et al.*, 2004; Schulze *et al.*, 2005b).

Following the delineation of the RSA, Lesotho and Swaziland into hydrologically interlinked Quinary Catchments (**Chapter 6**), the QDB has now been expanded to the Southern African Quinary Catchments Database (QnCDB). What follows is a summary description of key climatic and catchment input into the QnCDB. The focus of the climatic input is primarily on baseline historical conditions. The preparation of climate inputs derived from climate change scenarios will be discussed briefly in this chapter, with greater detail being provided in **Chapter 9** for the primary variables of rainfall and temperature.

7.2 Daily Rainfall Input per Quinary Catchment

7.2.1 Estimations of daily rainfall values for simulations under baseline climatic conditions

In 2004 Lynch compiled a comprehensive up-to-date database (1950-2000) of quality controlled (and infilled where necessary) rainfall data consisting of > 300 million rainfall values from 12 153 daily rainfall stations in southern Africa. From this database, a rainfall station had to be selected for each of the 5 838 Quinary Catchments, with that station's data considered representative of the daily rainfall of that Quinary.

This was achieved by assuming that the previously selected station representing the rainfall of the parent Quaternary Catchment would also represent the three Quinary Catchments within the Quaternary. The selection of the stations representing the Quaternary Catchments was described in Schulze *et al.* (2005b) and involved first determining the centroid of each of the Quaternary Catchments. The Daily Rainfall Extraction Utility (Kunz, 2004) was then used to extract the 10 closest rainfall stations to each catchment's centroid. These 10 stations were ranked by the Kunz (2004) Utility using 10 reliability criteria, with the best ranked station being subjected to further manual evaluation. In total, 1 244 stations were selected, the daily rainfall values from which were to "drive" the hydrology of the 1 946 Quaternaries. Reliability tests (Warburton and Schulze, 2005) showed the average reliability of the rainfall stations selected to be 79.2 %, with the highest reliability of a chosen station being 100% and the lowest reliability of a chosen rainfall station being 23.9%. Nearly 50% of the selected rainfall stations had a reliability of 95% or higher (Warburton and Schulze, 2005), with poorest reliability found to be in Lesotho, the Western Cape fold mountains region and along the northeastern border of the RSA with Mozambique. By implication, one rainfall station often had to "drive" the hydrology of numerous Quaternaries.

In response to further research during the course of this project, the representative (or “driver”) station for 11 Quaternary Catchments was changed in order to improve the representation of rainfall in those catchments. This resulted in the total number of driver stations reducing from 1 244 to 1 240. These 1 240 stations were then used to generate the daily rainfall of the 5 838 Quinary Catchments according to the assumption made above, viz. that each Quaternary Catchment driver station would also represent the rainfall of the associated three Quinary Catchments.

Multiplicative rainfall adjustment factors were then determined for each Quinary Catchment and applied to the driver station’s daily records in order to render the driver station’s daily rainfall to be more representative of that of the Quinary. In this way a unique 50 year daily rainfall record was created for each of the 5 838 Quinaries for application in hydrological simulation modelling. The adjustment factors were derived by first calculating the 12 spatial averages of all the one arc minute ($\sim 1.7 \times 1.7$ km) gridded median monthly rainfall values (determined by Lynch, 2004) within a Quinary Catchment. The ratio of these catchment average median monthly rainfalls to the driver station’s median monthly rainfalls was then calculated to arrive at 12 monthly adjustment factors.

7.2.2 *Estimations of daily rainfall values for simulations with future climate scenarios*

For climate change studies a similar approach was adopted, whereby suitable driver stations were identified from the 2 642 stations for which “present climate” (1971-1990) daily rainfall values, as well as those for an “intermediate future” (2046-2065) and a more “distant future” climate (2081-2100), had been empirically downscaled to station level for five Global Circulation Models (GCMs) by the Climate Systems Analysis Group (CSAG) at the University of Cape Town. In total 1 061 driver stations were identified, of which 1 023 were also used in representing the baseline (historical) climate above. As was the case for the baseline historical climate, the data for the above 1 061 driver stations were adjusted to better represent the rainfall of each Quinary Catchment, resulting in the development of a unique representative rainfall record for each Quinary. It was assumed that the monthly adjustment factors calculated for the baseline historical climate would also be applicable under the GCM derived climates considered (present, intermediate future and distant future). This assumption was made in the absence of fine resolution (e.g. one arc minute) national grids of median monthly rainfall for these present, intermediate future and more distant future periods which would be required if adjustment factors specific to those periods were to be calculated.

7.3 Daily Temperature Input per Quinary Catchment

7.3.1 *Estimations of daily values of maximum and minimum temperatures for simulations under baseline climatic conditions*

Daily maximum and minimum temperature values facilitate estimations to be made, implicitly or explicitly, of solar radiation, vapour pressure deficit and potential evaporation (Schulze, 2007), and with those variables plus rainfall as input into hydrological models such as *ACRU*, the generation of soil moisture content, runoff and/or irrigation demand becomes possible.

Procedures outlined in detail by Schulze and Maharaj (2004) enable the generation of a 50 year historical time series of daily maximum and minimum temperatures at any unmeasured location in RSA, Lesotho and Swaziland at a spatial resolution of one arc minute of latitude/longitude ($\sim 1.7 \times 1.7$ km) for the 429 700 grid points covering the region. In summary, the underlying temperature database was made up of daily, quality controlled records from > 970 temperature “control” stations, extended to a common 50 year period, viz. 1950-1999 (Schulze and Maharaj, 2004). Infilling and/or

extension of records to the common 50 year period at each of the control stations took account of independent month-by-month maximum and minimum temperature lapse rates (i.e. rates of change of temperature) from 12 lapse rate regions identified in southern Africa (Schulze, 1997), and from carefully chosen target stations at which similarities in the variability of daily temperature values with those from the control station was the key criterion. At each of the 429 700 grid points the maximum and minimum temperatures were computed for each day of the 50 year data period from two selected, independent (i.e. in different quadrants), temperature stations. The daily values from these two stations were then averaged in order to modulate any biases (from lapse rates or station data) emanating from either of the two stations' generated records.

Representative grid points from the study of Schulze and Maharaj (2004) were determined to represent each of the 5 838 Quinary Catchments covering the study area. The selection of the representative grid points was achieved by first calculating the mean altitude of each Quinary from a 200 m Digital Elevation Model. Grid points with altitudes similar to those of the catchment means, and located as close as possible to the catchment centroids (grid points preferably within the catchment), were then selected to represent each of the Quinary Catchments.

In summary, the above determination of daily maximum and minimum temperatures for the Quinary Catchments represents a two-step approach with

- first, the generation of a 50 year daily maximum and minimum temperature dataset at 429 700 raster points from > 970 control stations (with data quality checked and infilled), and
- secondly, the selection of individual grid points to represent each Quinary Catchment.

Based on the results of tests performed, the algorithm applied to select grid points (second bullet point, above) incorporated an exponential decay in the influence of altitude with distance from the point of interest, rather than the linear decay employed when selecting target stations for infilling of missing values at the control stations (control stations were used in the generation of the temperature grid; bullet point one, above).

The resulting 50 year series of daily maximum and minimum temperatures for each Quinary Catchment was then also used in the generation of daily estimates of solar radiation and vapour pressure deficit and from these, daily values of reference potential evaporation as well as potential crop evapotranspiration could be computed on a Quinary Catchment-by-Catchment basis).

7.3.2 *Estimations of daily values of maximum and minimum temperatures for simulations with future climate scenarios*

For climate change studies, empirically downscaled daily maximum and minimum temperature values from 404 stations common to all five GCMs used in this study (cf. **Chapter 9**) were supplied by CSAG for "present climate" (1971-1990) daily temperature values, as well as those for an "intermediate future" (2046-2065) and a more "distant future" climate (2081-2100). Two stations were selected to represent daily maximum and minimum temperatures in each of the Quinary Catchments. The selection algorithm developed for this purpose was, as in **Section 7.3.1**, also based on distance between the stations and the Quinary centroids, together with the difference in altitudes of the stations relative to the catchment mean altitude. The same month-by-month maximum and minimum lapse rates (for the 12 lapse rate regions identified in southern Africa by Schulze, 1997) which were applied in the generation of the temperature grid of Schulze and Maharaj (2004) were applied to the daily values from the two selected temperature stations. A weighted average of the adjusted temperatures from the two stations was then calculated to represent temperature in each Quinary Catchment. A 20

year time series of daily maximum and minimum temperature values was generated for each GCM for the three climatic periods for each of the 5 838 Quinary Catchments covering southern Africa.

7.4 Estimation of Daily Values of Solar Radiation per Quinary Catchment

7.4.1 Estimations of daily values of solar radiation for simulations under baseline climatic conditions

Variations in the amount of solar radiation (R_s) in time and over space causes all atmospheric movement and change, and solar radiation is thus ultimately the generator of all weather and climate. Additionally, agricultural (i.e. higher order) plants utilise the visible portion of the solar radiation to produce carbohydrates (dry matter, or yield) out of water and CO_2 during the process of photosynthesis, and from the above it becomes patently obvious that solar radiation is a major determinant of crop development and yields and it is, therefore, a major input variable in commonly used crop yield models such as CERES-Maize (Ritchie *et al.*, 1998). Hydrologically, of the three factors determining the processes of evaporation and transpiration, viz. solar radiation, vapour pressure deficit and wind, solar radiation is under most conditions the dominant factor, frequently explaining up to 80% of the variation in potential evaporation. It is, therefore, the major input variable to physically based methods for estimating potential evaporation, such as the Penman (1948) method and its variant, the Penman-Monteith method (Monteith, 1981), which has internationally become the *de facto* standard technique for estimating crop potential evapotranspiration.

In the absence of an adequate network of solar radiation stations with long quality controlled records, as is the case over much of southern Africa, R_s may be estimated from daily maximum (T_{mxd}), and minimum (T_{mnd}), temperatures (Richardson and Reddy, 2004). Under clear sky conditions high solar radiation loadings reach the earth's surface, resulting in rapid *warming* of the surface/atmosphere (i.e. high T_{mxd}), but with clear sky conditions also allowing terrestrial infrared (longwave) radiation to escape into space at night, enabling rapid *cooling* of the surface/atmosphere (i.e. low T_{mnd}), which in turn results in a large temperature range, T_{ra} (i.e. $T_{mxd} - T_{mnd}$). Conversely, cloudy conditions and rainfall reduce day time surface solar radiation (because of a lower T_{mxd}), with the clouds also absorbing and re-radiating more terrestrial radiation at night, thereby moderating the cooling rate, resulting in a lower T_{ra} (i.e. $T_{mxd} - T_{mnd}$). Hence T_{mxd} and T_{mnd} , particularly also when expressed through T_{ra} , are highly suitable surrogate variables for use in estimating R_s .

Because it is fundamentally sound, the Bristow and Campbell (1984) equation was used as a point of departure to estimate solar radiation in southern Africa from temperature. This equation essentially describes solar radiation as an exponential asymptotic function of daily T_{ra} as follows:

$$R_s = aR_a [1 - \exp(-bT_{ra}^c)]$$

where

- R_a = extraterrestrial radiation,
- = f (the solar constant, the earth's radius vector, latitude and solar declination, i.e. an expression of time of year),
- a = clear sky atmospheric transmissivity of R_a ,
- = 0.75 in the Bristow and Campbell equation, and which accounts for the depletion of R_a due to scattering by atmospheric aerosols and the pure atmosphere (Rayleigh extinction), as well as absorption by water vapour,

while

b, c = empirical constants governing the depletion of the solar beam due to cloudiness and rainfall, and for which daily T_{ra} is used as an estimator on the premise that cloudy/rainy conditions are associated with high atmospheric humidity and hence a low diurnal T_{ra} while under clear skies high temperature ranges prevail.

However, two modifications were made to the Bristow and Campbell equation by Schulze and Chapman (2007a) to improve estimates of R_a in southern Africa, the first being a modification of the clear sky transmission constant 0.75 by a water vapour related extinction function in the form of

$$1 - 1/T_{ra}^a$$

based on the premise that the higher the water vapour content (and by inference the lower the temperature range), the more the clear sky extinction would be. Clear sky solar radiation was thus expressed as

$$R_s = 0.75 R_a [1 - 1/T_{ra}^a]$$

with the exponent 'a' optimised from > 8 000 clear sky solar radiation observations from four defined solar radiation zones across southern Africa (Schulze and Chapman, 2007a).

The second modification accounted for intra-annual and regional variations in the Bristow and Campbell (1984) extinction expression for cloudy and rainy days (i.e. $[1 - \exp(-bT_{ra}^c)]$) by optimising the empirical constants 'b' and 'c' using > 40 000 daily solar radiation observations from 24 southern African stations each with quality checked R_s data. A month-by-month modification of b and c for each of southern Africa's four solar radiation zones resulted in marked improvements in estimates of R_s on cloudy and rainy days (Schulze and Chapman, 2007a).

With a well verified temperature based method of estimating daily values of solar radiation, the 50 year daily maximum and minimum temperature series generated at each of 429 700 grid points over southern Africa could then be used to estimate 50 years of daily R_s values at each of those points. For baseline hydrological simulations with the Quinary Catchments database the same representative points that were selected for daily temperature estimates (**Section 7.3.1**) were used and the daily R_s values at those points were then input into the database.

7.4.2 Estimations of daily values of solar radiation for simulations with future climate scenarios

The 20 year series of daily maximum and minimum temperatures generated for each of the three climate scenarios for each GCM and for each Quinary Catchment (cf. **Section 7.3.2**), were used in combination with the temperature based equations described in **Section 7.4.1** to produce corresponding 20 year series of daily solar radiation.

7.5 Estimation of Daily Values of Vapour Pressure Deficit per Quinary Catchment

7.5.1 Estimation of daily values of vapour pressure deficit for simulations under baseline climatic conditions

Daily values of vapour pressure deficit (VPD) are required when modelling potential evapotranspiration using the Penman-Monteith equation (Penman, 1948; Monteith, 1981). By definition,

$$VPD = e_a - e_d$$

where e_d = actual vapour pressure (kPa),
and e_a = saturated vapour pressure (kPa)
= $0.6108 \exp [17.27 T / (T + 237.3)]$ according to Tetens (1930), and
with T = air temperature (°C).

In estimating daily values of VPD the actual VP, e_d , which has been shown to be a conservative climate element (Chapman, 2004) and which may be derived at any specified location in southern Africa from well verified monthly regression equations (Schulze and Chapman, 2007b) based on four spatial variables (*viz.* latitude, longitude, distance from the ocean, altitude) plus one temporal variable (daily temperature range), is held constant at that location for a given month. The fluctuating day-to-day daily temperature values at that location are then used with the Tetens (1930) formula given above to calculate a daily saturated VP, e_a . From e_d and e_a daily values of VPD can then be computed.

Using the above equations and approach, the 50 year daily maximum and minimum temperature series generated at each of 429 700 grid points over southern Africa could then be used to estimate 50 years' daily VPD at each of those points. For baseline hydrological simulations with the Quinary Catchments database the same representative points that were selected for daily temperature estimates (**Section 7.3.1**) were used and the daily VPD values at those points were then input into the database.

7.5.2 Estimations of daily values of vapour pressure deficit for simulations with future climate scenarios

The 20 year series' of daily maximum and minimum temperatures generated for each of the three climate scenarios for each GCM and for each Quinary Catchment (cf. **Section 7.3.2**), were used in combination with the equations and approaches described in **Section 7.5.1** to produce corresponding 20 year series' of daily vapour pressure deficit.

7.6 Estimation of Daily Values of Reference Potential Evapotranspiration per Quinary Catchment

7.6.1 Estimation of daily values of reference potential evapotranspiration for simulations under baseline climatic conditions

The capacity of air to take up water vapour (with this capacity increasing with temperature and decreasing with humidity), the amount of energy available for the latent heat used in the process of evaporation (with the energy provided mainly by solar radiation) and the degree of turbulence in the lower atmosphere (related to wind) are the three factors which create an *atmospheric demand* and when this demand can be met fully, e.g. when soils are wet and vegetation covers the ground completely and is growing actively, *potential evapotranspiration* (E_p) occurs. There are many methods of estimating E_p , ranging from complex physically based equations to simple measurements and even simpler surrogates based on single variables such as temperature. These methods all yield different answers under different climatic conditions, and a *reference potential evaporation*, E_r (with its inherent advantages and defects), therefore has to be selected as that evaporation against which other methods must be adjusted appropriately. In simulating the hydrological landscape with a vegetative cover and/or under irrigation, the physically based FAO (1992) version of the Penman-

Monteith equation (Penman, 1948; Monteith, 1981) has now become the *de facto* international standard of what is termed *reference crop evapotranspiration*, replacing the A-Pan and other techniques. It is defined as

“The rate of evapotranspiration from a hypothetical crop with an assumed crop height of 0.12 m, a fixed canopy resistance of 70 s.m⁻¹ and albedo of 0.23, which would closely resemble evapotranspiration from an extensive surface of green grass cover of uniform height, actively growing, completely shading the ground and not short of water” (p.12).

The estimates of the Penman-Monteith equation as used in the Quinary Catchments Database are based on

- daily maximum and minimum temperatures, and hence daily saturated vapour pressures, generated over southern Africa on a 1' x 1' (~ 1.7 x 1.7 km) raster for 50 years, based on research by Schulze and Maharaj (2004) which has been summarised in **Section 7.3**,
- month-by-month gridded values of vapour pressure deficit for southern Africa, summarised in **Section 7.5**, and
- daily gridded values of solar radiation determined for southern Africa by modifications to the Bristow and Campbell (1984), as described by Schulze and Chapman (2007a) and summarised in **Section 7.4**.

The original form of the Penman-Monteith equation (Monteith, 1981) may be written as

$$\lambda ET_o = \frac{\Delta(R_n - G) + \rho c_p (e_a - e_d) / r_a}{\Delta + \gamma(1 + r_c / r_a)}$$

where	λET_o	=	latent heat influx of evaporation (kJ/m ² /s),
	R_n	=	net radiation flux at surface (kJ/m ² /s),
	G	=	soil heat flux (kJ/m ² /s),
	ρ	=	atmospheric density (kg/m ³),
	c_p	=	specific heat moist air (kJ/kg/°C),
	$(e_a - e_d)$	=	vapour pressure deficit (kPa),
	r_c	=	crop canopy resistance (s/m),
	r_a	=	aerodynamic resistance (s/m),
	Δ	=	slope of the vapour pressure curve (kPa/°C),
	γ	=	psychrometric constant (kPa/°C), and
	λ	=	latent heat of vaporisation (MJ/kg).

Adapting the above equation to the given definition of reference crop evapotranspiration, and multiplying out constants according to derivations and formulae given in FAO (1992), the above equation may be simplified to the following formula:

$$E_{rpm} = \frac{0.408\Delta R_n + Y \frac{900}{T_{xd} + 273} u_2 (e_a - e_d)}{\Delta + Y(1 + 0.34u_2)}$$

Where	E_{rpm}	=	reference crop evaporation (mm/day),
	R_n	=	net radiation at the crop surface (MJ/m ² /day),
	T_{xd}	=	average daily air temperature (°C) at screen height, and

u_2 = daily mean windspeed at 2 m height (m/s), defaulted (in the absence of measurements) to 1.6 m/s,

with the other variables defined as above.

Using the above equations, the 50 year daily maximum and minimum temperature series generated at each of 429 700 grid points over southern Africa could then be used to estimate 50 years' daily reference crop evapotranspiration by the Penman-Monteith technique at each of those points. For baseline hydrological simulations with the Quinary Catchments database the same representative points that were selected for daily What remains is for T_{xd} , Δ , γ , R_n , e_d and e_a to be formulated. The formulations are a combination of the simplifications of FAO (1992) derived equations and empirical expressions developed specifically from southern African research. Thus,

T_{xd} = mean daily air temperature ($^{\circ}\text{C}$)
= $(T_{mxd} + T_{mnd}) / 2$, with
 T_{mxd} = daily maximum temperature ($^{\circ}\text{C}$) (cf. Schulze and Maharaj, 2004; summary in **Section 7.3.1**)
 T_{mnd} = daily minimum temperature ($^{\circ}\text{C}$) (cf. Schulze and Maharaj, 2004; summary in **Section 7.3.1**)
 e_a = saturated vapour pressure (kPa)
= $0.6108 \exp\{(17.27 T_{xd}) / (T_{xd} + 237.3)\}$,
 e_d = actual vapour pressure (kPa)
= empirically derived for South Africa on a month-by-month basis (cf. Schulze and Chapman, 2007b; with summary in **Section 7.5.1**),
 Δ = delta, i.e. slope of vapour pressure curve (kPa/ $^{\circ}\text{C}$)
= $[4098\{0.6108 \exp((17.27 T_{xd}) / (T_{xd} + 237.2))\} / (T_{xd} + 237.3)^2]$,
 γ = psychrometric "constant" (kPa / $^{\circ}\text{C}$)
= $0.665 / (10^3 P_a)$, with
 P_a = atmospheric pressure (kPa), determined from altitude, viz.
= $101.3[(293 - 0.065z) / 293]^{5.26}$, with
 z = altitude (m) above mean sea level,
 R_n = $R_{sn} - R_{lw}$, with
 R_{sn} = net shortwave (solar) radiation ($\text{MJ/m}^2/\text{day}$)
= $(1 - 0.23) R_s$, with albedo of short grass assumed to be 0.23, and
 R_s = $0.75 R_a(1 - 1/T_{ra}^{2.5})[1 - \exp(-b T_{ra}^c)]$, with
 R_a = extraterrestrial solar radiation, from tables or standard formulations (cf. Schulze and Chapman, 2007a; summarized in **Section 7.4.1**),

temperature estimates (**Section 7.3.1**) were used and the daily Penman-Monteith values at those points were then input into the database.

7.6.2 Estimations of daily values of reference crop evapotranspiration for simulations with future climate scenarios

The 20 year series of daily maximum and minimum temperatures generated for each of the three climate scenarios for each GCM and for each Quinary Catchment (cf. **Section 7.3.2**), were used in combination with the temperature based equations and approaches described in **Section 7.6.1** above to produce equivalent 20 year series of daily reference crop evapotranspiration.

7.7 Hydrological Soils Attributes

Hydrological models require soils information as input. Being a threshold based model, *ACRU* (Schulze, 1995 and updates) needs input values on the following soils variables:

- thicknesses (m) of the topsoil and subsoil;
- soil water contents (m/m) at
 - saturation (porosity),
 - drained upper limit (also commonly referred to as field capacity), and
 - permanent wilting point (i.e. the lower limit of soil water availability to plants);
- rates of “saturated” drainage from topsoil horizon into the subsoil, and from the subsoil horizon into the intermediate groundwater zone, and the
- erodibility of the soil.

Values of these variables have been derived by Schulze and Horan (2007) using the AUTOSOILS decision support tool (Pike and Schulze, 1995 and updates) applied to the ISCW soils database (SIRI, 1987 and updates) for each of the soil mapping units, called Land Types, which cover South Africa, on the basis that the hydrological properties of all the soil series making up an individual Land Type were area-weighted. For each Quinary Catchment the values of the hydrological soils variables required by the *ACRU* model were derived from the Land Types identified in that Quinary, again on an area-proportioned basis.

7.8 Hydrological Attributes of Baseline Land Cover Types

In any hydrological impact studies the hydrological attributes of baseline land cover types are required in order to simulate any changes in hydrological responses when the baseline land cover is converted to new land uses or new forms of land management. For South Africa, Lesotho and Swaziland the 70 Acocks' (1988) Veld Types are a recognised baseline (i.e. reference) land cover for application in hydrological impact studies (cf. Schulze, 2004; 2007).

Based on a set of working rules for determining the water use coefficient, interception per rainday, root distribution, a coefficient of infiltrability, an index of suppression of soil water evaporation by a litter/mulch layer and a soil loss related vegetal cover factor, month-by-month values of these attributes given in Schulze (2004; 2007) were incorporated into the Quinary Catchments Database for each of the 70 Acocks' Veld Types covering southern Africa. For each of the 5 838 Quinaries in the database the spatially most dominant Veld Type was then selected as the representative baseline land cover.

7.9 Hydrological Attributes of Land Use Categories

For studies on present-day or anticipated future hydrological responses which are impacted upon by anthropogenic changes in land use and management (e.g. afforestation, land degradation, urbanisation, enhanced tillage or tillage practices), hydrological attributes of such land uses need to be input into models such as *ACRU*. Currently, in addition to the 70 Acocks baseline land covers, month-by-month values of the water use coefficient, leaf area index (where available), interception per rainday, root distribution, a coefficient of infiltrability and a soil loss related vegetal cover factor, are being assigned to each category of the National Land Cover (2000) 49-fold classification of land use in a hydrologically consistent manner.

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CHAPTER 8 METHODS 3: MODELLING IMPACTS OF CLIMATE CHANGE ON THE HYDROLOGICAL SYSTEM: MODEL REQUIREMENTS, SELECTION OF THE ACRU MODEL, ITS ATTRIBUTES AND COMPUTATIONS OF MAJOR STATE VARIABLES AND OUTPUTS

R.E. Schulze

8.1 The Significance of the Water Sector in Climate Change Studies

The superpositioning of a potential “speeding up” and “energizing” of the hydrological cycle through climate change in an era when water management is already in a state of flux, does not simplify matters for decision makers in the water sector, particularly if one bears in mind the amplification effects of changes in rainfall attributes on hydrological responses and the vital links of water to the aquatic ecosystem, to other cycles (e.g. nitrogen, carbon) and other sectors (e.g. agriculture, transport, health or risk management). Appropriate hydrological models will become an increasingly important tool in addressing the consequences of many of these changes. The first question which presents itself is what is required, by way of process representations, of a suitable model for assessing impacts of climate change on the hydrological system (Schulze, 2005), secondly, once a model has been selected, what its attributes are and thirdly, how the major state variables and outputs which are relevant to modelling responses to projected future climates, are computed.

8.2 Model Requirements for Effective Climate Change Impact Studies on the Hydrological System

8.2.1 What constitutes the hydrological system that we need to model?

From the above introduction it becomes patently clear that modelling impacts of climate change on hydrological responses involves two “streams” of action, but which need to be merged (Schulze, 2005). This is illustrated in **Figure 8.1**. On the one hand,

- climate change demands an innovative approach to modelling *hydrological processes*, because perturbations in the drivers of these processes (e.g. ΔP , ΔT and ΔCO_2 and its feedbacks on transpiration) will result in changes in evaporative demand, changes in the partitioning of rainfall into the different runoff components (e.g. stormflow, baseflow) and, hence, changes in water quality (e.g. sediment yield).
- In essence these response changes occur on the *landscape component* of the catchment, on which natural land cover and soils properties may already have been altered by human actions.
- Key climate change issues in regard to the landscape component include direct changes in responses of runoff processes to the altered climatic drivers, but also indirect changes, for example, to the hydrological baseline against which impacts are assessed, or to altered water quantity and quality responses resulting from spatial changes in land use patterns associated with new climates (Schulze, 2005).

On the other hand,

- *water resources practitioners/managers* have to grapple, now and in a future climate, with balancing supply of water (be it from rivers, groundwater, impoundments, return flows or water transfers) with demand for water (e.g. from basic human and ecological needs to requirements for the urban/industry sectors, power and irrigation) and to allocate available water, now and in a

future climate, in a sustainable manner through holistic planning, i.e. Integrated Water Resources Management, IWRM.

- In most instances allocation involves manipulations of the *channel component* of the catchment through “controls” of storage, releases and routing of water.
- Key climate change related challenges generally revolve around engineering issues of changes in supply/demand, limits to the design of hydraulic structures in regard to system failure, as well as around environmental consequences of changes in natural flow regimes, including in-stream flow requirements and other abiotic/biotic effects downstream (Schulze, 2005).

Wedged, in a manner of speaking, between the landscape and channel are the

- *transitional components* of the hydrological system, such as the wetlands, riparian zones and estuaries.
- These components are frequently in delicate equilibria, which may “flip” as a consequence of landscape and channel manipulations, and under conditions of global warming these elements may become even more fragile and/or sensitive.
- Key challenges in regard to wetlands, riparian zones and estuaries will be to assess changes in their functioning and to the ecosystem goods and services they provide (Schulze, 2005).

For pro-active management all the above challenges have to be met explicitly or implicitly by appropriate hydrological modelling. Some model requirements are, therefore, listed and discussed below.

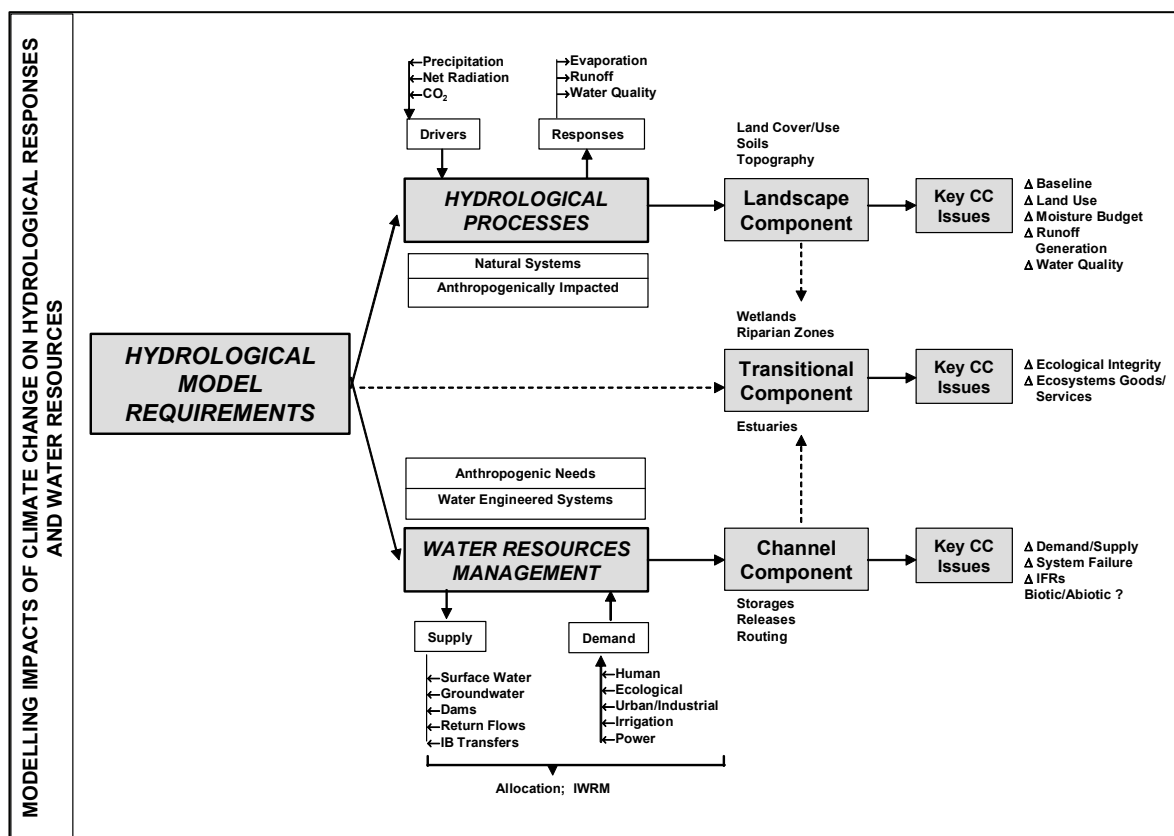


Figure 8.1 Hydrological model requirements under conditions of climate change (Schulze, 2005)

8.2.2 What demands does this place on process representations in, and the structure of, hydrological models?

8.2.2.1. The need to be able to model explicitly the dynamics of different streamflow generation mechanisms

Streamflow is not simply streamflow, for its various components are generated by different mechanisms and are generated from different (and dynamic) source areas within a catchment, both of which may alter with climate change. The different streamflow components display different properties and hydrological functions (Schulze, 2005), with

- *overland flows*, which may be generated either from connected (adjunct) impervious areas, or from saturated zones of variable areas, or when rainfall intensities exceed infiltrability, with these flows having short residence times of minutes to hours, being event-based, removing/transporting sediments and other surface material (e.g. fertilizers, pesticides, industrial pollutants) and being critical in peak discharge estimations as well as in water quality determinations; whereas
- *subsurface stormflows* having slower response times and different water chemistries; and
- *baseflows*, which are sustained by recharge from preferential zones within a catchment, having long memories, displaying slow decay, a different chemistry again and having a different criticality in that they maintain different biological functions to those of stormflows.

The proportions of these components of streamflow will vary, *inter alia*, with changed attributes of rainfall patterns, altered land uses and antecedent catchment wetnesses associated with climate change (Schulze, 2005). Because of their variable residence times/lags, as well as their different origins within a catchment and their associated properties of water quantity and quality, these streamflow components need to be *modelled explicitly as distinct individual components* (and not by empirical hydrograph separation) if certain key questions in their responses to climate change, and IWRM in general, are to be answered adequately.

8.2.2.2 The need to distinguish clearly between landscape based and channel based processes

Within morphologically similar landscapes, hydrological processes down hillslopes tend to be *repetitive*, with the hillslope elements of the catchment being the generators of streamflow in its different forms.

- Catchment (as distinct from channel) processes under conditions of climate change need to be modelled separately by *water budgeting* procedures, which are not always fully understood (Schulze, 2005).
- Channel processes, on the other hand, tend to be *additive* with catchment size, are *attenuated* by channel characteristics of slope, shape and roughness as well as by transmission losses to floodplains, banks and alluvial beds and by open water evaporation, may be *manipulated* (e.g. by abstractions, diversions and impoundments, **Figure 8.1**) and need to be modelled *hydraulically* with often complex equations describing relatively well understood relationships.

If catchment and channel processes, as well as those of transitional hydrological features (the riparian zones, wetlands and estuaries) are not separated explicitly in models used for climate change impact studies, and IWRM in general, scaling problems emerge in parameterisations between smaller and larger catchments (Schulze, 2005).

8.2.2.3 *The ability to model hillslope processes*

Be it impacts of fertilizer or pesticide movement, the different generation mechanisms of streamflow or sediment production, or water demand by land uses in riparian vs upslope areas, these are all influenced by hillslope hydrological processes and pathways with the respective thresholds, rates, accumulations and feedbacks of the different elements making up the landscape, viz. the crest, scarp, midslope, footslope and riparian zone. The hillslope elements and their accumulative downslope interactions need to be represented in a conceptually sound manner in order to answer prognostically the many questions which catchment managers will be posing in the near future, and which are likely to be exacerbated by climate change (Schulze, 2005).

8.2.2.4 *The ability to model the different processes which may dominate in different climatic regimes*

Southern Africa displays a wide climatic range with annual precipitations from < 50 mm to > 3 000 mm, some falling as low intensity rain, sometimes as snow and some associated with high intensity convective storms, coupled with high intra- and inter-seasonal variability, often a strong seasonality. This precipitation falls on physiographies ranging from steep montane to undulating hills to plains. All this implies a highly variable spatio-temporal conversion of precipitation to streamflow, as well as a regionally and seasonally variable partitioning of the streamflow into overland flows, subsurface stormflows, baseflows or even snowmelt and, in the case of the groundwater table, this may or may not be “connected” to the channel, depending again on season and location.

For example, groundwater recharge may be through the soil matrix in more humid areas or by transmission losses in more arid zones, while evaporation losses may be dominated by riparian zone processes, or by transpiration, or by soil water evaporation, depending on climatic regimes, or evaporation rates may be influenced strongly by slope and aspect. By way of another example, mountain catchments’ hydrology may be dominated by poorly understood precipitation: altitude gradients which vary with rain vs. snow, rainfall intensities, numbers of rainfall days and event magnitudes, since all of these change with elevation.

Climate change will alter the spatial patterns of hydroclimatic regimes. Directly, or by surrogate means, the various processes which under present climatic conditions may be present or absent, or may dominate in specific hydroclimatic regimes, will have to be encapsulated in model process representations for effective modelling of climate change impacts on water resources (Schulze, 2005).

8.2.2.5 *The ability to model different intensities of land management practices*

Identical broad land cover categories can produce significantly different hydrological responses, depending on the level or intensity of management practice. Thus, for example, grassland in overgrazed vs well managed condition can change sediment yield by a factor of 4 or more (Schulze, 2003), or annual crops grown on fields with vs without contour banks, or under conventional vs conservation tillage practices, can yield significantly different magnitudes of runoff, in addition to changes in the partitioning of runoff into stormflows vs baseflows (Schulze, 2005).

In an era when, in southern Africa, streamflow reduction activities, best management practices, payments for ecosystems goods and services and the polluter pays principle are integral components of water management, and where land uses are likely to shift spatially in future with the result that adaptive management practices are likely to be applied, models have to be able to simulate

differences in land use management practices realistically under present and, particularly, future climatic conditions.

8.2.2.6 *The need for a daily time step, conceptual-physical, process-based and non-linear dynamic response model*

In order to model potential impacts of global change on hydrological processes and responses (the top component in **Figure 8.1**), in line with the model requirements discussed above, such a model needs the following attributes (Schulze, 2005):

- be *conceptual* in that it conceives of a one or multi-dimensional system in which important processes and couplings are idealised, and
- be *physical* to the degree that the physical processes are represented explicitly through observable variables (Eagleson, 1983).
- The model should, at minimum, be functional (i.e. threshold based, with initial and boundary conditions) in its process representation (Schulze, 1998).
- Hydrological processes should account for present and future climate exchanges of water vapour, CO₂ and energy (e.g. precipitation attributes, streamflow generation responses, evaporation and transpiration together with its CO₂ driven feedbacks for modelling plant-soil interactions of future climates),
- modified by characteristics of the
 - *soil* (surface infiltrability, subsurface transmissivity of soil water and water holding capacity),
 - *land cover and land use/management* (e.g. with above-ground attributes related to intra-seasonal biomass; surface attributes of soil protection by litter/mulch or of tillage practices; below-ground attributes relating to root distribution), and
 - *topographic features* of the landscape (altitude, slope, aspect, toposequence and topographic position).
- The model should reproduce non-linear and scale-related catchment responses explicitly, where these may be associated with
 - *spatial heterogeneity* in surface processes (e.g. topography, soils, rainfall, evaporation, land use),
 - *non-linearities* responding to episodic events (e.g. rainfall), cyclicity (e.g. seasons, evaporation), hillslope processes (e.g. on and below surface), immediate responses (e.g. surface runoff from connected impervious areas; saturated overland flow), rapid responses (e.g. stormflow), ephemerality (e.g. discontinuous flows), continuous responses (e.g. groundwater movement) and delayed responses (e.g. baseflow),
 - *thresholds which are required* for surface and subsurface streamflow processes to commence, and
 - *dominant processes which change with scale or human interference*, including emerging properties (e.g. advection) and representations of disturbance regimes (e.g. drainage of fields, changes in streamflow regimes resulting from dam construction / abstractions / return flows), gradual changes in land use intensification over time (e.g. agriculture and urbanisation), or in extensification (e.g. overgrazing impacts), or abrupt changes resulting from fires or flooding.
- As such the model should essentially be devoid of parameter adjustment, since parameterisation “hides” the reason for changes in hydrological responses while a conceptual-physical model “provides” the reason and should, in theory, not require external calibration procedures to produce robustly acceptable results.
- Furthermore, for most operational modelling, simulations should take place at daily time steps since the day is the shortest *universal natural time step*, and climate variables from GCMs are

nowadays output at daily values. Furthermore, diurnality encapsulates (albeit not perfectly) many hydrologically related processes which are important in climate change studies (e.g. evaporation, transpiration and many discrete rainfall events), while many operational decisions are currently, and in future climates will also be, made according to daily conditions (e.g. irrigation, reservoir releases) and daily climate data for baseline hydrological conditions are readily available.

- Model output for impact studies of projected climate change within a framework of IWRM will have to address management conflicts for a range of spatial scales from upslope vs downslope impacts, upstream vs downstream impacts, as well as those within vs between Water Management Areas (Schulze, 2005).

The major advantage of such daily time step, conceptual-physical, non-linear response models is that, because of their high level of process representation and physically based boundary conditions, they may be used with confidence in extrapolations involving “what-if” scenarios of hitherto unmeasured land management strategies, extreme events or climate variability which may be associated with global change and which are essential ingredients of IWRM.

8.3 The ACRU Modelling System

8.3.1 Model attributes

The ACRU agrohydrological modelling system (Schulze, 1995; Schulze and Smithers, 2004 and updates), which has been, and is currently being, used extensively in IWRM and climate change studies in southern Africa, was selected as the preferred simulation tool as it complies with many of the premises and principles outlined above and is centred around the following objectives and attributes (Figures 8.2 and 8.3):

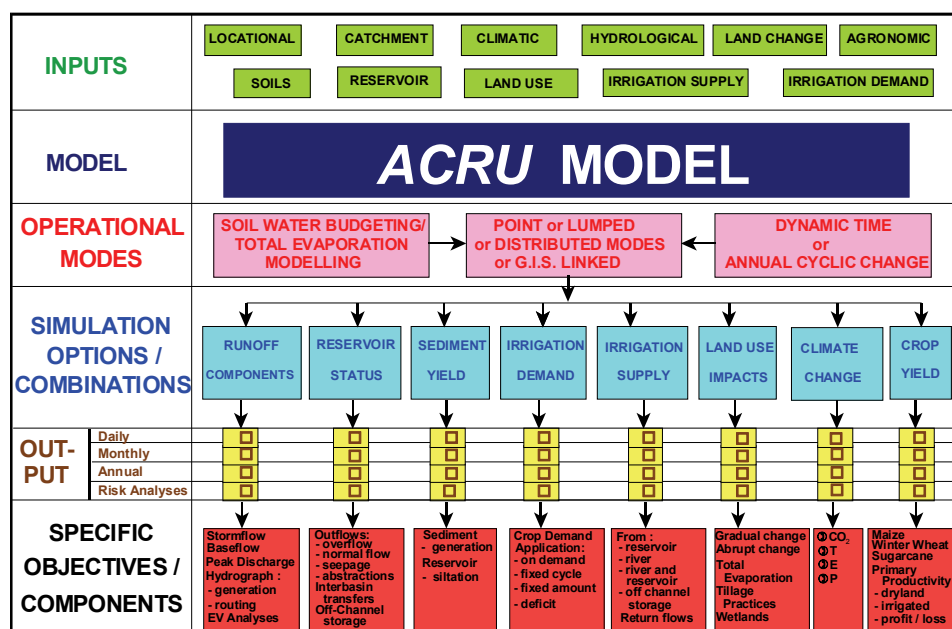


Figure 8.2 The ACRU agrohydrological modelling system: Concepts (After Schulze, 1995)

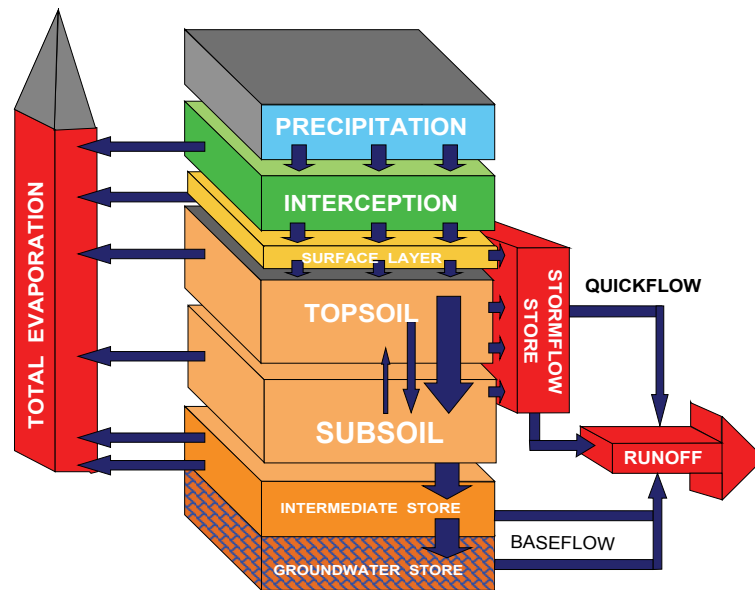


Figure 8.3 The ACRU agrohydrological modelling system: General structure (After Schulze, 1995)

- It is a *daily time step, conceptual-physical* model,
- with variables (rather than optimised parameters values) estimated from physically based characteristics of the catchment, and
- with the model revolving around daily *multi-layer soil water budgeting*.
- As such, the model has been developed essentially into a versatile total evaporation model (**Figure 8.3**), structured to be highly sensitive to climate drivers and to land cover, land use and management changes on the soil water and runoff regimes, and with its water budget being responsive to supplementary watering by irrigation, to changes in tillage practices, enhanced atmospheric CO₂ concentrations associated with climate change, or to the onset and degree of plant stress, which may change with global warming.
- ACRU is a *multi-purpose* model which integrates the various water budgeting and runoff production components of the terrestrial hydrological system (**Figure 8.2**). It can be applied as a versatile model for design hydrology (including flow routing through channels and dams), crop yield estimation, reservoir yield simulation, ecological requirements, wetlands hydrological responses, riparian zone processes, irrigation water demand and supply, water resources assessment, planning optimum water resource utilisation/allocation, conflict management in water resources and land use impacts - in each case with associated risk analyses – and all of which can respond differently with climate change.
- ACRU can operate at multiple scales as a *point* model or as a *lumped* small catchments model, on large catchments or at national scale as a *distributed* cell-type model with flows taking place from “exterior” through “interior” cells according to a predetermined scheme, with the facility to generate individually requested outputs at each subcatchment’s exit.
- The model includes a *dynamic input option* to facilitate modelling of hydrological responses to climate or land use or management changes in a time series, be they long term/gradual changes (e.g. urbanisation or climate trends), or abrupt changes (e.g. construction of a dam), or changes of an intra-annual nature (e.g. crops with non-annual cycles).
- The ACRU model has been linked to the Southern African National Quaternary and Quinary Catchments Databases for applications at a range of scales in South RSA, Lesotho and Swaziland for climate change impacts and other studies.

8.3.2 The ACRU model's water budget in summary

In the model, rainfall that is not abstracted as plant interception or removed as stormflow, enters through the surface layers to reside in the topsoil, which when filled to beyond its drained upper limit (i.e. "field capacity"), redistributes (i.e. drains) excess water into subsequent soil horizons at a rate dependent on respective horizon wetnesses, soil textures and/or impeding layers. Slow, unsaturated up- and downward moisture redistribution is also accounted for. Evaporation occurs simultaneously from the various soil horizons, dependent on root mass distribution, atmospheric demand and the respective horizon wetnesses. Stormflow is generated, after initial abstractions, as a function of the magnitude of rainfall and the soil's wetness from a defined critical depth of soil (**Section 8.4.2**), while baseflow is generated from excess water percolating through the bottom of the active root zone into the intermediate (vadose) and then the groundwater stores, from where baseflow is produced by slow release (as a decay function) of water into streams connected to the groundwater (**Section 8.4.3**).

8.4 Simulations, with the ACRU System, of Major State Variables and Model Output which are Important in Climate Change Studies

The crucial state variable which will respond to perturbations in climate is that of soil water content, while the hydrologically significant output variables are stormflow, baseflow and sediment yield. The methodologies of simulating these with the ACRU model are described below.

8.4.1 Estimation of critical threshold levels of soil water content

In hydrology information on soil water content is vital, since

- the need to irrigate occurs when the actual soil water content, θ , is lower than the critical soil water content at which plant stress commences, viz. θ_{fs} ; furthermore,
- when the plant is stressed, the total evaporation from the plant/soil system, E , is lower than the maximum evaporation, E_m , which is a condition that can take place when either
 - an excess of soil water is present and plants cannot transpire (grow) at their maximum because they suffer from anoxia (lack of oxygen), with this occurring when $\theta > DUL$, i.e. the soil's Drained Upper Limit, or when
 - a deficiency of soil water is experienced because $\theta < \theta_{fs}$; and also
- the soil water deficit, S , defined here as the difference between soil water content at saturation, θ_{PO} , and actual soil water content, θ , is a crucial input variable in the equation used in the ACRU model (Schulze, 1995) to simulate stormflow from a given rainfall event (**Section 8.4.2**).

On the other hand, in agricultural operations, the trafficability of farm machinery in a field and the degree of soil compaction are further considerations in which soil water content plays a determining role. Furthermore, soil water deficits have a marked effect on photosynthesis. All these factors are likely to change in future climates.

A major objective of utilising ACRU to assess soil water content *per se* is to establish the mean number of days (e.g. per annum) on which the soil water content would exceed, or be below, specific critical thresholds (Schulze *et al.*, 2007). These thresholds were

- excess plant water stress,
- no plant water stress,
- mild plant water stress, and
- severe plant water stress.

Each of these thresholds are described below and illustrated in **Figure 8.4**.

- *Excess plant water stress* is the condition a plant experiences when soil water content, θ , exceeds that held at the soil's Drained Upper Limit (*DUL*), i.e. θ_{DUL} , resulting in the soil becoming saturated. The result of this condition is a limit in the plant's ability to transpire at its maximum rate, caused by a state of anoxia (lack of oxygen) resulting from conditions of excess soil water (Dijkhuis and Berliner, 1988). Excess plant water stress is thus expressed as:

$$\theta > \theta_{DUL}$$

on a given day, with the day's total evaporation, E , then reducing to below its maximum, E_m , depending on the amount of excess water, with the potential to reduce total evaporation to 0.3 of E_m when the soil is totally saturated (Dijkhuis and Berliner, 1988).

- *No plant water stress* is the condition when the plant is not under any soil water stress and is therefore able to transpire at its maximum rate, i.e. $E = E_m$ or $E/E_m = 1$, as in **Figure 8.4**. These conditions occur when the soil water content equals or drops below that at the soil's *DUL*, but equals or exceeds the soil water content at a specified fraction of total Plant Available Water (*PAW*) at which plant stress commences, viz. θ_{fs} , and which in the case of most vegetation types is set at ~ 0.5 *PAW*. Total *PAW* is defined here as the difference between soil water held at *DUL*, i.e. θ_{DUL} , and that held at the plant's Permanent Wilting Point or Lower Limit, i.e. θ_{LL} (Dunne and Leopold, 1978). Therefore, the conditions under which no plant water stress occurs on a given day are expressed as

$$\begin{aligned} \theta_{DUL} \geq \theta \geq \theta_{fs} \text{ or} \\ \theta_{DUL} \geq \theta \geq 0.5(\theta_{DUL} - \theta_{LL}). \end{aligned}$$

- *Mild plant water stress* is the condition whereby the plant is mildly stressed as a result of the soil water content being below the stress fraction, θ_{fs} , but it is still able to transpire at a rate defined as being equal to, or in excess of, 20% of its maximum evaporation, i.e.

$$\begin{aligned} \theta_{fs} > \theta \geq 0.2 E/E_m, \text{ i.e. computationally equal to} \\ \theta_{fs} > \theta \geq 0.6 (\theta_{fs} - \theta_{LL}). \end{aligned}$$

- *Severe plant water stress* may be defined as the soil water content at which the plant is only able to transpire at a rate of below 20% of its maximum evaporation, i.e.

$$\theta < 0.2 E_m$$

which in this case, with θ_{fs} being set to 0.5 *PAW*, equates to

$$\theta < 0.6 (\theta_{fs} - \theta_{PWP}).$$

For each level of plant water stress the equations given above are applied with standard *ACRU* soils input values of soil horizon thicknesses and soil water retention at saturation, drained Upper Limit and the Permanent Wilting Point.

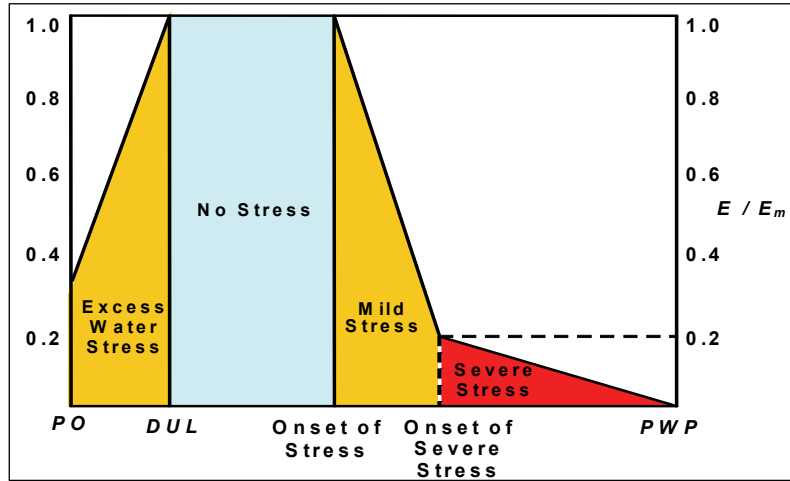


Figure 8.4 Schematic of different levels of plant water stress (Schulze, Hull and Maharaj, 2007)

8.4.2 Generation of stormflow in the ACRU model

Stormflow, Q_s , is defined as the water which is generated in a catchment either at, or near, the surface from specific rainfall events, the magnitude and frequency of which are projected to change with future climates. Stormflow is computed in the *ACRU* model (Schulze, 1995 and updates) in mm equivalents as

$$Q_s = (P_n - I_a)^2 / (P + I_a + S) \quad \text{for } P_n > I_a$$

in which

- P_n = net rainfall (mm), i.e. gross (measured) rainfall minus canopy interception losses,
- I_a = initial abstractions (mm) before stormflow commences, consisting mainly of that infiltration which occurs between the beginning of the rainfall event and the beginning of storm runoff, plus any depression storage, and
- S = the soil's potential maximum retention (mm), which is equated to the soil water deficit and is an expression of the wetness or dryness of the soil.

In *ACRU*, the soil water deficit S is calculated by the daily multi-layer soil water budget, and for computations of stormflow a critical soil depth, D_{sc} (m) is defined from which S is determined. The depth of D_{sc} accounts for the different dominant runoff producing mechanisms which may vary in different climates, as well as with catchment land uses, tillage practices, litter/mulch cover and soil conditions. For all hydrological simulations in this project, D_{sc} was defined as the thickness of the topsoil.

A major determinant of initial abstractions is soil moisture content. In order to eliminate estimations of both I_a and S in the equation above, I_a is expressed as a coefficient, c , of S , where c is an index of infiltrability into the soil and varies with rainfall intensity (thunderstorms $\equiv$ smaller c), tillage practice and surface cover/litter/mulch (Schulze, 1995). For all simulations in this project, the c of I_a was input as that value assigned on a month-by-month by Schulze (2004) for the 70 baseline land cover types (Acocks, 1988) found in southern Africa.

Not all stormflow generated from a rainfall event exits the catchment on the same day as the rainfall occurs, and the fraction that does depends on the size of the catchment, the catchment's slope and other factors (Schulze, 1995). This necessitates a stormflow response coefficient, F_{sr} , to be input,

which controls the “lag” of stormflows and is effectively an index of interflow. For all simulations on all subcatchments in this project, F_{sr} was set at 0.3, a value which has been found experimentally to be typical in South Africa for use at the spatial scale of Quinary Catchments.

8.4.3 Generation of baseflow in the ACRU model

Unlike many other models which compute baseflow indirectly from total runoff hydrographs with an empirically derived “separation curve”, *ACRU* computes baseflow explicitly from recharged soil water stored in the intermediate/groundwater zone (Schulze, 1995). The number of recharge events and the magnitude of the stored water will be altered with changed rainfall attributes in future climates. In *ACRU* the stored water is derived from rainfall of previous events which has been redistributed through the various soil horizons and has drained into the intermediate/groundwater store when the deepest soil horizon’s water content exceeds its drained upper limit (field capacity). The *rate of drainage* of this “excess” water out of the deepest soil horizon *into the groundwater store* depends on that horizon’s soil texture class, which in this project has been input to vary from catchment to catchment according to soil attributes.

The rate of release of water from the groundwater store into the stream is determined by a release coefficient, F_{bff} , which is dependent *inter alia* on the geology, area and slope of the catchment. F_{bff} operates as a “decay” function which is input for a catchment as a single value, but based on experiences with *ACRU* in many catchment studies, F_{bff} is then either enhanced, retained or decreased internally in *ACRU*, dependent on the previous day’s groundwater store (cf. Schulze, 1995). For all simulations in this project an experimentally determined typical value of F_{bff} for southern Africa of 0.009 was used.

8.4.4 Generation of sediment yield in the ACRU model

Soil erosion is already a serious problem in southern Africa (Lorentz and Schulze, 1995) and under conditions of changed climates, particularly if rainfall intensities were to increase, sediment yields could increase markedly. To date no simple method has yet been found to estimate sediment yield from a catchment. Complex deterministic models are available, however, these are limited in their application owing to their reliance on calibration, which essentially eliminates them for climate change impacts assessments. *ACRU* has imbedded within it the daily stormflow event based Modified Universal Soil Loss Equation, MUSLE (Williams, 1975), which has been widely verified world-wide and in South Africa (Kienzie *et al.*, 1997) and which renders it a suitable technique for application in climate change studies.

In the MUSLE, sediment yield at any Quinary (or Quaternary) Catchment outlet may be estimated by

$$Y_{sd} = \alpha_{sy} (Q_v \times q_p)^{\beta_{sy}} K \times LS \times C \times P$$

where	Y_{sd}	=	sediment yield (t) from an individual stormflow event,
	Q_v	=	stormflow volume for the event (m^3),
	q_p	=	peak discharge for the event (m^3/s),
	K	=	soil erodibility factor (t h/N/ha),
	LS	=	slope length and gradient factor (-),
	C	=	cover and management factor (-), and
	P	=	support practice factor (-).

The MUSLE coefficients, α_{sy} and β_{sy} are location specific (Simons and Sentürk, 1992), but internationally accepted default values set at 8.934 for α_{sy} and 0.56 for β_{sy} were assumed in sediment yield simulations for this project.

When the sediment yield option is selected, the peak discharge for each Quinary Catchment (QnC) needs to be simulated for each stormflow event. For these simulations the SCS peak discharge equation, modified by Schulze and Schmidt (1995), is used. In this equation

$$q_p = 0.2083Q_s A / 1.83 L$$

where q_p = peak discharge (m^3/s),
 Q_s = stormflow depth (mm),
 A = catchment area (km^2),
 L = catchment lag (response) time (h),
 $L = (A^{0.35} MAP^{1.1}) / (41.67 S_{\%}^{0.3} f_{30}^{0.87})$,
 with MAP = mean annual precipitation (mm),
 $S_{\%}$ = average catchment slope (%), and
 f_{30} = 30 minute rainfall intensity (mm/h) for the 2 year return period.

Information needed for each Quinary Catchment thus includes

- the mean catchment slope, $S_{\%}$, which was derived for each Quinary from a 200 m Digital Elevation Model;
- the 30 minute rainfall intensity (mm/h) for the 2 year return period, f_{30} , which for historical climates can be computed for southern Africa by multiplying the 2 year return period one day rainfall depth by an intensity multiplication factor given in **Table 8.1** and derived for Weddepohl's (1988) four rainfall intensity distribution zones of South Africa (Schulze, 1995; Lorentz and Schulze, 1995);

Table 8.1 Multiplication factors used in the computation of f_{30} for the four rainfall distribution zones of South Africa (Source: Schmidt and Schulze, 1987)

Intensity Multiplication Factor	Rainfall Intensity Distribution Zone			
	1	2	3	4
	0.430	0.664	0.974	1.236

- stormflow volume for each event (cf. **Section 8.4.2**) simulated from baseline land cover (Acocks, 1988) with the hydrological attributes of the 70 Acocks Veld Types, as given by Schulze (2004);
- the soil erodibility factor, K , determined from the ISCW's soil land types using the AUTOSOILS program (Pike and Schulze, 1995 and updates) and mapped by Schulze and Horan (2007);
- the slope length and gradient function, computed internally in *ACRU* using catchment slope as input;
- the cover and management factor, C , as determined by Schulze (2004); and
- the support practice factor, P , not applicable for these simulations under baseline land cover conditions and thus set to 1.
- Of the sediment yield generated from a stormflow event on a given day, 45% is assumed to exit the QC on the day of the event and the balance released as a decay function.

8.5 Conclusions: On the Suitability of the *ACRU* Model for Climate Change Impact Studies on Hydrological Processes and Water Resources

The requirements for the “ideal” model with which to assess potential impacts of climate change, in the real world of complex hydrological interplays, are both manifold and stringent. On the one hand changes to non-linear processes with feedforwards and feedbacks need to be accounted for, on the other hand the realities of the operational world of water engineered systems to meet demand with supply in a sustainable manner through manipulations of the system by storages, losses, transfers, return flows and downstream controls dominates many developed catchments (Schulze, 2005).

The *ACRU* modelling system meets many of the criteria/requirements discussed in previous sections. Its conceptual-physical structure, operating on a daily time step and its multi-purposeness are without doubt attributes weighing in favour of its selection as a suitable model, as is its potential as a tool in resolving water management conflicts (e.g. land use impacts, water allocation, impacts on/of wetlands and reservoirs) at scales from small catchment to national, as testified by over 100 references in this regard in Schulze and Smithers (2004).

ACRU accounts explicitly for stormflow generation and for recharge into the intermediate and groundwater zones. However, processes involving baseflow releases and interflow contributions are still represented by simple algorithms only, and which require more research. *ACRU* operates simultaneous runoff generating routines for the pervious fraction of the catchment (stormflow, baseflow) and the impervious fraction (connected and unconnected to the channel system) in addition to separate routines for stormflow, percolation and return flows from irrigated areas.

The model contains the option (applicable mainly to larger catchments) of distinguishing between

- landscape-based processes (also by disaggregating the catchment into interlinked relatively homogeneous response units such as Quinary Catchments; cf. **Chapter 6**),
- channel-based processes (including separate reservoir water budget which can account also for gains through inter-basin transfers and losses by evaporation, seepage, abstractions and environmental demands, and the
- transitional zones of wetlands and riparian zones,

but with hillslope processes at this stage distinguishing only between the riparian and non-riparian zones.

ACRU has been applied in wide-ranging climatic regimes from arid (Arizona) to tropical (Ghana), to temperate climates in which snowmelt is important (Germany). Certain processes require further refinement, e.g. channel transmission losses, interflow and hillslope processes in general, and many of the water quality routines which have been developed for *ACRU* by researchers (e.g. N, P, *E. coli*) are yet to be fully operationalised (Schulze, 2005).

Despite several shortcomings, *ACRU* is nevertheless believed to be a modelling system highly suitable for evaluating impacts of climate change on the hydrology and water resources of southern Africa.

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CHAPTER 9 METHODS 4: REPRESENTATION OF GRID AND POINT SCALE REGIONAL CLIMATE CHANGE SCENARIOS FOR NATIONAL AND CATCHMENT LEVEL HYDROLOGICAL IMPACTS ASSESSMENTS

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9.1 Objectives of This Chapter

Daily climate values from climate change scenarios produced for application at national and more local level impact assessments, were obtained from the Climate Systems Analysis Group at the University of Cape Town in both grid and point formats. Daily rainfall was the only variable available in the gridded format for the various climate scenarios, while the scenarios downscaled to point format included daily maximum and minimum temperature, in addition to daily rainfall. In order to apply these values from the climate scenarios in hydrological impacts assessments, techniques had to be developed to represent the scenarios at the scale of catchments, rather than at grid or point scales. The development of these techniques is described in this chapter. As rainfall was the only variable available for the climate scenarios in the gridded format, these scenarios were not applied in this study as hydrological modelling requires at least daily maximum and minimum temperatures to also be available. Instead, the rainfall values from the various climate scenarios in gridded format were evaluated with respect to “hydrologically relevant” rainfall statistics (cf. **Chapter 12**).

This chapter is divided into two main sections, devoted respectively to approaches adopted for representing gridded and point values from climate scenarios at catchment scale. Approaches for representing the daily values from the climate scenarios downscaled to point formats at catchment scale were briefly alluded to in **Sections 7.2 and 7.3 of Chapter 7** and are described in more detail in this chapter.

9.2 Gridded Regional Climate Change Scenarios

9.2.1 Description of gridded regional climate change scenarios

In climate change science, regional climate change scenarios are developed by downscaling global climate change scenarios which are coupled atmosphere-ocean GCMs. The gridded regional climate change scenarios developed by CSAG for application in this project were derived from global scenarios produced by six GCMs. Three of these GCMs were applied in the IPCC (2001) Third Assessment Report (TAR), while the other three were applied in the IPCC (2007) Fourth Assessment Report (AR4). In **Table 9.1** the names of the GCMs, the institutes who developed them, the relevant IPCC study (TAR or AR4) and links to further information, are given.

All of the future global climate scenarios were simulated based on the A2 emissions scenario defined by the IPCC Special Report on Emission Scenarios (SRES) (Nakićenović and Swart, 2000). This scenario of greenhouse gas emissions suggests that efforts to reduce global emissions this century are relatively ineffective. Regardless of the emissions scenario selected, a further increase of at least 0.6°C in global mean temperature is likely, owing to past greenhouse gas emissions (Hewitson *et al.*, 2005).

The regional climate change scenarios were developed by CSAG by empirically downscaling the GCM simulation output, and were produced at a quarter degree latitude x longitude spatial resolution for southern Africa. Empirical downscaling techniques involve deriving relationships between synoptic

scale and local climates using observational data, and then applying these relationships to GCM output to generate the higher resolution regional climate change scenarios (Hewitson *et al.*, 2005).

Table 9.1 Information on GCMs the global climate change scenarios of which were empirically downscaled by CSAG to a 0.25° grid for application in this project

Institute	GCM
Commonwealth Scientific and Industrial Organisation (CSIRO) / Marine and Atmospheric Research, Australia	Name: CSIRO IPCC Study: TAR Website: http://www.cmar.csiro.au/cgi-bin/abstract_srch.pl?abstract_available_7277
Max Planck Institute for Meteorology (MPI-M), Germany	Name: ECHAM IPCC Study: TAR Website: http://www.mpimet.mpg.de/en/wissenschaft/modelle.html
United Kingdom Meteorological Office (UKMO) / Hadley Centre for Climate Prediction and Research, UK	Name: HadAM IPCC Study: TAR Website: http://www.metoffice.gov.uk/research/hadleycentre/
NOAA / Geophysical Fluid Dynamics Laboratory (GFDL), USA	Name: GFDL IPCC Study: AR4 Website: http://data1.gfdl.noaa.gov/nomads/forms/deccen/
Center for Climate System Research (CCSR, University of Tokyo), National Institute for Environmental Studies (NIES), and Frontier Research Center for Global Change (FRCGC), Japan	Name: MIROC IPCC Study: AR4 Website: http://www.ccsr.u-tokyo.ac.jp/kyosei/hasumi/MIROC/tech-repo.pdf
Japan Meteorological Agency / Meteorological Research Institute (MRI), Japan	Name: MRI-CGCM IPCC Study: AR4 Website: http://www.mri-jma.go.jp/Dep/cl/cl4/publications/yukimoto_CGER2002.pdf

Regional climate change scenarios were developed for “present”, “intermediate future” and more “distant future” climates represented by the following time periods defined by the IPCC:

- present climate: 1960-1990 for both AR4 and TAR models
- intermediate future climate: 2046-2065 for AR4 models only
- distant future climate: 2081-2100 for AR4 models
2070-2100 for TAR models

With the exception of the TAR derived scenarios under the intermediate future climates, all the regional scenarios included a daily time series of rainfall for each climatic period. In analyses of the AR4 scenarios in this project (cf. **Chapter 12**), only 20 years of the present climate data were used in comparative studies with the intermediate and distant future climates in order to consider an equal number of years in all periods. The last 20 years of the present climate (1971-1990) were selected for this purpose so that time interval between the present climate and the intermediate future climate would be more similar to the interval between the intermediate future and the distant future climates. In comparative analyses of the TAR scenarios (cf. **Chapter 12**) the full 30 year periods for the present and distant future climates were used.

9.2.2 Methodology to represent gridded regional scenarios at the scale of Quaternary Catchments

At the time that the School of BEEH obtained the gridded regional climate change scenarios from CSAG, the Quaternary Catchments, described in **Chapter 6**, had not yet been delineated. Therefore the gridded regional scenarios were linked to the existing Quaternary Catchments (QCs).

In order to represent the gridded regional climate change scenarios at Quaternary Catchment scale, individual pixels were selected from the 0.25° regional scenario grids to represent each of the 1 946 QCs in southern Africa. In doing this, the first step was to compare the relative spatial scale of the regional climate grids to those of the QCs. In **Figure 9.1**, a grid with the same spatial resolution as those of the regional climate scenarios has been overlaid by a map of the QCs. A close-up view of the area highlighted by the blue rectangle in **Figure 9.1** is given in **Figure 9.2**. **Figure 9.1** shows that the larger QCs in the region (mostly in the more arid Northern Cape Province of South Africa) are generally greater in area than the 0.25° climate scenario pixels, while in other physiographically more complex areas, such as that shown in **Figure 9.2**, the QCs and pixels have areas that are of a similar size. It was undesirable to simply average the data contained in the pixels falling within a catchment, since this would exacerbate the differences in temporal rainfall variability between climate model (areal) and station (point) rainfall data (Chen *et al.*, 1996; Osborn and Hulme, 1997). Instead, the approach adopted was to assign a single representative pixel to each QC. In this regard, it was assumed that the pixel containing the centroid of a QC be selected to represent the climate of that catchment.



Figure 9.1 A 0.25° resolution grid overlaid by the Quaternary Catchment boundaries

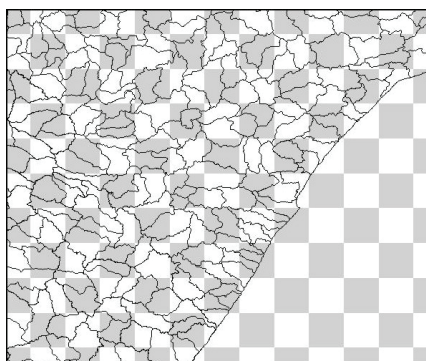


Figure 9.2 Close-up view of the area highlighted in **Figure 9.1**

9.3 Point Scale Climate Change Scenarios

9.3.1 Description of point scale climate change scenarios

The point scale climate change scenarios developed by CSAG for application in this project were derived from global scenarios produced by five GCMs, all of which were applied in the IPCC's (2007) Fourth Assessment Report (AR4). In **Table 9.2** the names of the GCMs, the institutes which developed them, the year of the first publication of results from each model and links to further information are given. All of the future global climate scenarios that were downscaled by CSAG to point scale were, like the grid based downscaling (cf. **Section 9.2.1**), based on the A2 emissions scenario defined by the IPCC SRES (Nakićenović and Swart, 2000).

The point scale climate change scenarios were generated by empirically downscaling the GCM simulation output. The points at which scenarios were produced were the locations of the climate stations used in the empirical downscaling process. Scenarios of daily rainfall were produced at 2 642 southern African stations (**Figure 9.3**), while daily maximum and minimum temperature scenarios were produced at 440 and 427 stations, respectively (**Figure 9.4**). The lack of climate stations over Lesotho and Swaziland is of concern in climate change studies, but this reflects the reality of the relatively sparse observation networks of high quality, long duration and readily available data in those countries.

The point scale climate change scenarios were generated for the same periods that gridded regional AR4-derived scenarios were developed (cf. **Section 9.2.1**), except that the present climate period commenced a year later (1961) and extended for an additional 10 years up to 2000. The same assumption regarding the number of years considered in the present climate, when comparing this period to the other climate scenarios (e.g. in **Chapters 12, 13 and 14**) was made, viz. that a consistent 20 years be considered for all climates. The period 1971-1990 was again selected for the present climate, with the period 1961-1980 not considered as the time interval between the present climate and the intermediate future climate would be very long (85 years) relative to the interval between the intermediate future climate and the distant future climate (35 years). The period from 1981-2000 was not considered as this period may already have experienced a strong climate change signal, making it less suitable as a baseline period. The periods considered in comparative analyses in this report were therefore:

- present climate: 1971-1990
- intermediate future climate: 2046-2065
- distant future climate: 2081-2100.

9.3.2 Methodology to represent point scale scenarios of rainfall at the scale of Quinary Catchments

The representation of the point scale scenarios of rainfall at the scale of Quinary Catchments was achieved using the same "driver" station approach adopted for baseline historical conditions (cf. **Section 7.2.1**). The number of driver stations previously selected for baseline conditions and for which data on future rainfall scenarios were also available, was determined to be 1 023 (from the set of 2 642 possible stations). These driver stations were assumed to represent future climatic conditions in their associated Quinary Catchments, which numbered 4 863. For the remaining 975 Quinary Catchments (out of the total of 5 838 covering southern Africa) alternative driver stations for which future rainfall scenarios were available needed to be selected. The criteria used to re-select these driver stations were:

- Distance from the Quinary Catchment's centroid,
- Mean annual precipitation compared with that of observed data,
- Altitude difference between the station and the Quinary,
- Length of the observed record, and
- Reliability of the observed record.

Table 9.2 Information on GCMs the global climate change scenarios of which were empirically downscaled by CSAG to point scale for application in this project

Institute	GCM
Canadian Center for Climate Modelling and Analysis (CCCma), Canada	Name: CGCM3.1(T47) First published: 2005 Website: http://www.cccma.bc.ec.gc.ca/models/cgcm3.shtml
Meteo-France / Centre National de Recherches Meteorologiques (CNRM), France	Name: CNRM-CM3 First published: 2004 Website: http://www.cnrm.meteo.fr/scenario2004/indexenglish.html
Max Planck Institute for Meteorology (MPI-M), Germany	Name: ECHAM5/MPI-OM First published: 2005 Website: http://www.mpimet.mpg.de/en/wissenschaft/modelle.html
NASA / Goddard Institute for Space Studies (GISS), USA	Name: GISS-ER First published: 2004 Website: http://www.giss.nasa.gov/tools/modelE
Institut Pierre Simon Laplace (IPSL), France	Name: IPSL-CM4 First published: 2005 Website: http://mc2.ipsl.jussieu.fr/simules.html

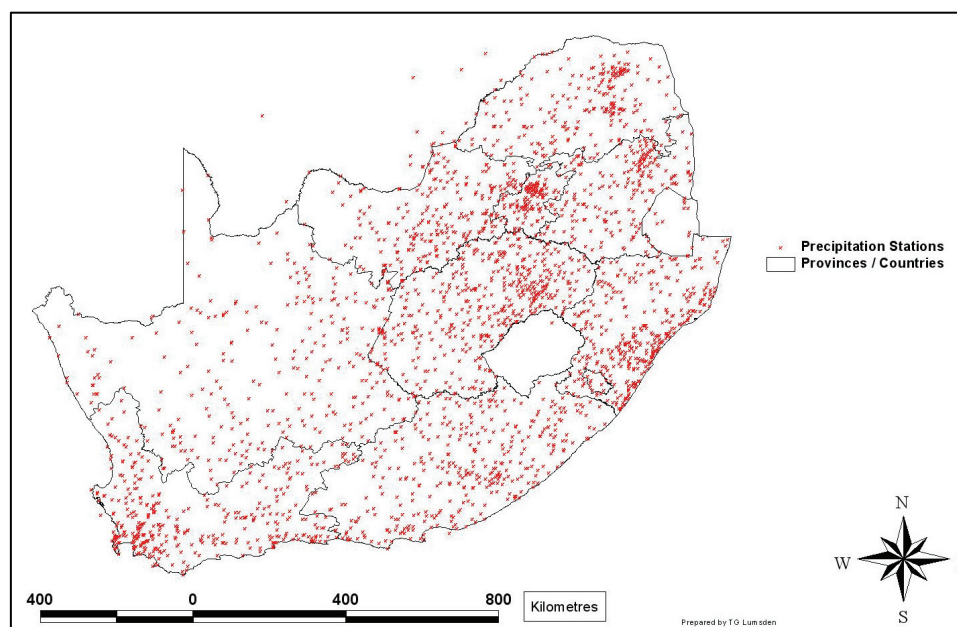


Figure 9.3 Climate stations for which point scale climate change scenarios for daily rainfall were developed

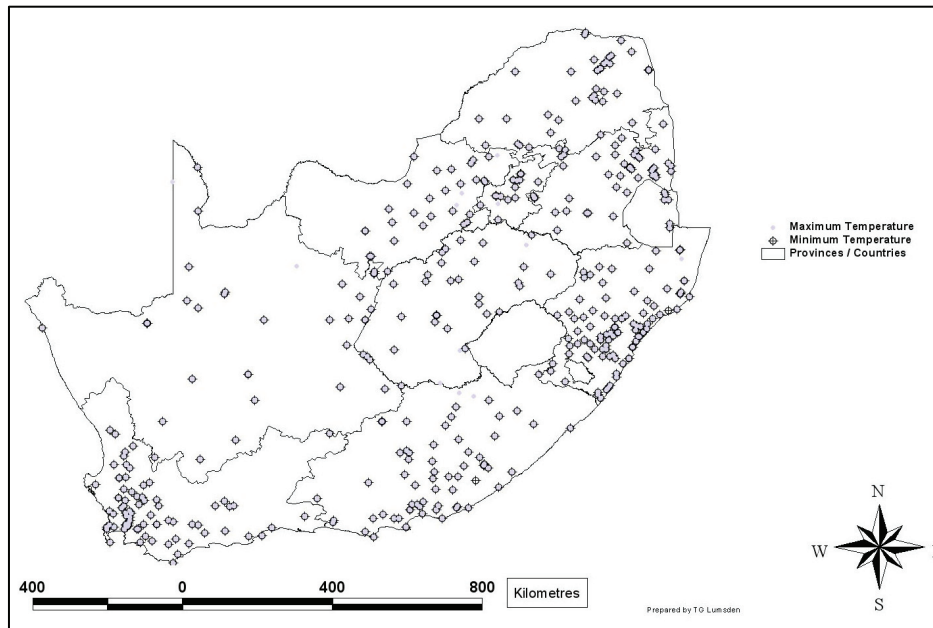


Figure 9.4 Climate stations for which point scale climate change scenarios for daily temperature were developed

Of the above 975 Quinaries, 687 were assigned to stations that already acted as driver stations for other catchments. The number of driver stations concerned numbered 134. The remaining 288 Quinaries were assigned to stations that had not previously been used as driver stations. This resulted in 38 new driver stations being selected. The total number of all rainfall driver stations used in assessing future rainfall impacts therefore numbered 1 061.

As was the case for the baseline historical climate (cf. **Section 7.2.1**), and alluded to in **Section 7.2.2**, the daily rainfall values for the above 1 061 driver stations were adjusted to better represent the rainfall of each Quinary Catchment, resulting in the development of a unique representative rainfall record for each Quinary. This was done on the assumption that the monthly adjustment factors calculated for the baseline historical climate (cf. **Section 7.2.1**) would also be applicable under the GCM derived climates considered (present, intermediate future and distant future). This assumption was made in the absence of *fine resolution* (e.g. one arc minute) national grids of median monthly rainfall for these new climate periods which would ideally have been required if adjustment factors specific to the periods were to have been calculated. In the calculation of the adjustment factors for the baseline historical climate, limits were placed on the magnitude of the adjustment factors to prevent unrealistic adjustments being made to the driver station data. These limits ensured that adjustment factors fell between 0.5 and 2.0. These limits were relaxed relative to previous studies (e.g. Schulze *et al.*, 2005; Schulze, 2007) where the factors were constrained to be between 0.7 and 1.3. The relaxed adjustments were deemed necessary because of the finer scale of modelling performed in this study (Quinary Catchments) relative to previous studies (Quaternary Catchments). Quaternary Catchment driver stations are now assumed to drive their component Quinary Catchments, which are often distinctly different from one another in their topographic characteristics (cf. **Table 6.1** in this report).

9.3.3 Methodology to represent point scale scenarios of temperature at the scale of Quinary Catchments

An examination of the climate stations for which scenarios of temperature change were obtained from CSAG revealed that there were 425 stations common to having both maximum and minimum temperature data sets. Of these 425 stations, 21 had immediately adjacent ‘twin’ stations with identical geographical coordinates (i.e. the same station, but reporting to two different data agencies). Since only one station at a particular location could be considered for application in hydrological modelling, the quality of the historical (observed) records of the 42 (21 x 2) implicated stations were analysed to identify the ‘better’ station at each location. This therefore resulted in 404 unique stations being identified for representation of maximum and minimum temperatures in the 5 838 Quinary Catchments across South Africa, Lesotho and Swaziland.

The methodology adopted to represent maximum and minimum temperatures at Quinary Catchment scale involved selecting the two most representative stations for each Quinary Catchment, and obtaining a daily weighted average of their data. Adjustments were simultaneously applied to each of the two stations’ data to account for differences between the stations’ altitudes and that of the respective Quinary. This was done using the adiabatic temperature lapse rates (i.e. the rate of change of temperature with altitude) which had been determined for each month of the year, and separately for maximum and minimum temperatures, by Schulze and Maharaj (2004) for 12 defined lapse rate regions in southern Africa (Schulze, 1997). Only temperature stations falling within the specific lapse rate region relevant to a particular Quinary Catchment were considered for representation of temperature in that catchment. In certain lapse rate regions, some stations were excluded from consideration based on altitude related criteria.

The algorithm to select the two most representative stations for a Quinary Catchment represented a modification of the algorithm developed in Schulze and Maharaj (2004) for selecting target stations for infilling of missing data at representative control stations (control stations were used in the generation of the 1 arc minute resolution daily maximum and minimum temperature grid for South Africa, Lesotho and Swaziland). The modified algorithm involved performing a preliminary suitability ranking of all stations considered in order to determine the five most suitable stations. This suitability ranking was sensitive to the distance of a station from the centroid of a catchment, together with the difference in altitude of the station relative to the catchment’s mean altitude. The suitability ranking was determined by the following series of equations:

$$DF = (1 - DIST/350)*0.9 + 0.1$$

where DF = distance factor, and

$DIST$ = distance between station and Quinary Catchment centroid (minutes of a degree), constrained to a maximum value of 350 minutes

and $AF = (1 - DALT/1500)*0.9 + 0.1$

where AF = altitude factor, and

$DALT$ = altitude difference between station and Quinary Catchment mean altitude (m), constrained to a maximum value of 1500 m

with $RF = (DF*10) + (AF*1)$

where RF = ranking factor.

DF was formulated in such a way that it would range between 0.1 (worst case where the station is 350 degree minutes or more away) and 1 (best case where the station coincides with the catchment's centroid). AF was formulated in such a way that it would range between 0.1 (worst case where the station has an altitude difference of 1500 m or more relative to the catchment's mean altitude) and 1 (best case where the station has the same altitude as that calculated for the catchment). The five stations with the highest RF values would therefore be selected according to the preliminary suitability ranking. The 350 minute and 1500 m thresholds were introduced to DF and AF , respectively, to ensure that stations met *minimum* criteria for *both* distance and altitude. Otherwise a station could rank well based on only one variable, while in reality it may have been unsuitable in terms of the other variable (e.g. small altitude difference combined with a large distance from the centroid). In the calculation of RF , DF was assigned a higher weighting than AF owing to its relative importance.

A final suitability ranking of the five stations identified above was then performed to determine the 'best' two stations in terms of *both* distance and altitude. To achieve this, the range in distances (relative to the catchment centroid) and altitude differences (relative to the mean altitude of the catchment) among the five stations was introduced into the calculation of DF and AF , as follows:

$$DF = (1 - (DIST - MIND)/(MAXD - MIND))*0.9 + 0.1$$

where $MIND$ = distance (m) between closest station and Quinary Catchment centroid, and
 $MAXD$ = distance between most distant station and Quinary Catchment centroid (m)

and $AF = (1 - (DALT - MINA)/(MAXA - MINA))*0.9 + 0.1$

where $MINA$ = difference in altitude between the station most similar in altitude to the Quinary Catchment mean altitude and the Quinary Catchment mean altitude (m), and
 $MAXA$ = difference in altitude between the station least similar in altitude to the Quinary Catchment mean altitude and the Quinary Catchment mean altitude (m).

DF becomes 1.0 (best) for the station closest to the Quinary's centroid. All other stations are ranked relative to this closest station as they are compared to the range in distance ($MAXD - MIND$). Similarly, AF approaches 1.0 (best) for stations at altitudes similar to that of the Quinary's mean altitude. Again, all other stations are ranked relative to this station ($MAXA - MINA$). This 'relative' ranking technique is superior to others because it compares each station to the 'best'. Hence, the distance and altitude thresholds used will vary from Quinary to Quinary and are not fixed, as in the preliminary station suitability ranking.

In the calculation of RF , more weighting was given to AF than previously, as it was assumed that the preliminary ranking would exclude stations that were unsuitable from a distance perspective. Hence:

$$RF = (DF*10) + (AF*3)$$

Having identified the two 'best' temperature stations to represent a Quinary Catchment, the data from these stations were then averaged in order to obtain the final temperature record for the catchment. This averaging was weighted according to the RF factor calculated for each station. As mentioned previously, adiabatic temperature lapse rates were also simultaneously applied to each station's data.

Checks identical to the ones done on historical data by Schulze and Maharaj (2004) were performed on the daily maximum (T_{mxd}) and minimum (T_{mnd}) temperature values from the GCMs to ensure that they would comply with certain logical requirements and those of the *ACRU* hydrological model. These checks were performed both before and after any adjustments (i.e. lapse rate adjustments and weighted averaging) were applied to the downscaled GCM data and they included the following:

- $T_{mxd} \leq T_{mnd}$
- $T_{mxd} - T_{mnd} < 1.5^{\circ}\text{C}$.

Although not a requirement of *ACRU*, an additional check was performed to highlight potentially unrealistic data in a southern African context, viz.

- $T_{mxd} < 0^{\circ}\text{C}$.

Where instances of the former two checks were found in the raw downscaled GCM values, the relevant days' temperature data were altered to comply with the requirements of *ACRU* (Schulze and Maharaj, 2004). Data were again checked after lapse rate adjustments and weighted averaging had been completed and, if necessary, altered to ensure compliance with the *ACRU* model input requirements. Where instances of the last check were found, no alteration to the maximum temperatures were made (before or after lapse rate adjustments and weighted averaging), but these instances were flagged for future reference.

By way of example, the results of the data checks for the ECHAM5/MPI-OM GCM are presented in **Table 9.3** and **Table 9.4** for instances *before* and *after* lapse rate adjustments and weighted averaging, respectively.

Table 9.3 Results of checks performed on the downscaled ECHAM5/MPI-OM maximum and minimum temperature values before application of lapse rate adjustments and weighted averaging

Climatic Period	Check	Total Number of Daily Occurrences	Total Number of Stations Implicated
Present	$T_{mxd} \leq T_{mnd}$	676	4
	$T_{mxd} - T_{mnd} < 1.5^{\circ}\text{C}$	158	4
	$T_{mxd} < 0^{\circ}\text{C}$	318	3
Intermediate Future	$T_{mxd} \leq T_{mnd}$	110	4
	$T_{mxd} - T_{mnd} < 1.5^{\circ}\text{C}$	144	5
	$T_{mxd} < 0^{\circ}\text{C}$	0	0
Distant Future	$T_{mxd} \leq T_{mnd}$	188	3
	$T_{mxd} - T_{mnd} < 1.5^{\circ}\text{C}$	302	4
	$T_{mxd} < 0^{\circ}\text{C}$	78	2

From **Table 9.3** and **Table 9.4** it is clear that the lapse rate adjustments and weighted averaging result in a higher number of daily occurrences of the various checks. In the case of the check for $T_{mxd} < 0^{\circ}\text{C}$, it is again emphasised that no 'corrections' were actually applied to these temperature values, neither before or after applying lapse rate adjustments. The lapse rates were, however, capped at $-10^{\circ}\text{C} / 1000 \text{ m}$ to minimise such occurrences. The effect of this capping is reflected in the results in **Table 9.4**.

Table 9.4 Results of checks performed on the downscaled ECHAM5/MPI-OM maximum and minimum temperature values after application of lapse rate adjustments and weighted averaging

Climatic Period	Check	Total Number of Daily Occurrences	Total Number of Quinary Catchments Affected
Present	$T_{mxd} \leq T_{mnd}$	889	33
	$T_{mxd} - T_{mnd} < 1.5^{\circ}\text{C}$	7552	141
	$T_{mxd} < 0^{\circ}\text{C}$	2417	210
Intermediate Future	$T_{mxd} \leq T_{mnd}$	335	20
	$T_{mxd} - T_{mnd} < 1.5^{\circ}\text{C}$	2967	125
	$T_{mxd} < 0^{\circ}\text{C}$	313	58
Distant Future	$T_{mxd} \leq T_{mnd}$	192	16
	$T_{mxd} - T_{mnd} < 1.5^{\circ}\text{C}$	2330	136
	$T_{mxd} < 0^{\circ}\text{C}$	578	138

9.4 Conclusions

This chapter has focused on approaches adopted for representing gridded and point climate change scenarios at catchment scale. The gridded scenarios are analysed in **Chapter 12** in regard to changes in hydrologically relevant statistics of rainfall across South Africa at Quaternary Catchment scale. The point scenarios are also subjected to similar analyses in **Chapter 12** at Quinary Catchment scale and are then further applied in analyses of changes in stream water temperature in the Thukela Catchment in **Chapter 13** and changes in indicators of hydrological alteration across southern Africa in **Chapter 14**.

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CHAPTER 10 METHODS 5: COMPUTATION OF WATER TEMPERATURE

K.R. Barichievsky and R.E. Schulze

10.1 Introduction to Modelling Water Temperature

Water temperature in streams and rivers has previously been identified (**Chapter 4**) as an important attribute of water quality and it controls the overall health of freshwater ecosystems (Morrill *et al.*, 2005). Unlike the flow indicator analyses which are analysed at the southern Africa scale (**Chapter 3**), the water temperature analyses are computationally very intensive and thus the water temperature indicator results are spatially analysed at the scale of only one Water Management Area in South Africa, *viz.* the Thukela Catchment, which has been described in detail in **Chapter 5**. In addition to the spatial analysis, a temporal investigation, by means of time series analyses, was performed on important water temperature related indicators and the methods and techniques used in these analyses are outlined **Sections 10.2-10.7**.

10.2 Datasets Required

In order to investigate the possible impacts of climate change on water temperature related indicators, the *ACRU* model was run with the climate datasets described in more detail in **Chapter 9**, *viz.*

- Baseline (i.e. historically observed) Climate (1971-1990),
- Present Climate from the ECHAM5 GCM (1971-1990), and
- Intermediate Future Climate (2046-2065) from ECHAM5, and a more
- Distant Future Climate (2081-2100) from ECHAM5.

After running the model for the above time periods, both daily individual subcatchment runoff and accumulated streamflows for the 258 Quinaries which constitute the Thukela Catchment were extracted from the *ACRU* output file. The values of both daily individual subcatchment runoff and accumulated streamflows were subsequently converted from mm equivalents to m³ using (sub)catchment area.

10.3 Modelling Maximum Water Temperature

For this project a stochastic approach was selected in order to model water temperature for each of the 258 Thukela Quinaries because data constraints would have ruled out deterministic approaches (cf. **Chapter 4**). For each of the 258 Quinaries the daily minimum and maximum air temperatures were extracted for the baseline, present, intermediate future and the more distant future climate scenarios and daily means of temperature were subsequently calculated. A linear regression model developed by Rivers-Moore *et al.* (2005) from South African data (**Chapter 4**) was then applied to daily means of temperatures for the four climate scenarios in order to calculate daily maximum water temperature.

10.4 Cascading Water Temperature down the Catchment

As water cascades down the catchment from its headwaters to the ocean, or from an Upper, through Middle to the Lower Quinary, it usually warms, and thus variation in water temperature occurs longitudinally down a river system with headwaters typically at lower temperatures than those in lowland areas (Dallas, 2008). Water temperature is dynamic since water is always mixing within the

river channel as well with water from incoming tributaries. However, this complicates water temperature modelling. In order to mimic this mixing, maximum water temperature is therefore calculated daily for each individual Quinary Catchment as well as at the exit points of two or more Quinaries. Furthermore, at an exit point or a confluence the river segment with the greater volume will have more influence on the combined downstream water temperature than the tributary with the smaller volume of water. This weighted cascading therefore continues longitudinally down a river system and consequently the water temperature of the Quinary flowing into the sea, or out of South Africa into a downstream country, or into a river which forms an international border with South Africa, is influenced by the water temperature of all the upstream catchments.

10.5 The Water Temperature Index

The Water Temperature Index (WTI) of a (sub)catchment is the product of daily maximum water temperature ($^{\circ}\text{C}$) and the simulated flow (m^3) for that day. The WTI was developed in combination with the cascading of water temperature in order to create a weighting system at the exit of two Quinaries or at the confluence of rivers in order to give the larger flow more influence on the combined WTI (**Figure 10.1**). For simplicity it is assumed that perfect mixing occurs at these exits and/or confluences.

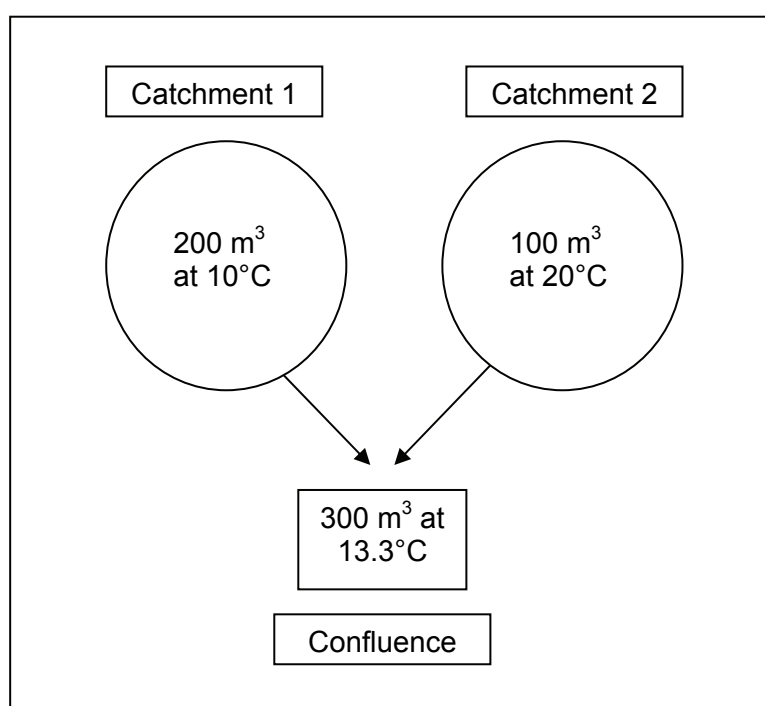


Figure 10.1 An example of cascading streamflow and water temperature at the confluence of two rivers

10.6 Calculating Maximum Mixed Water Temperature

The maximum mixed water temperature is calculated by using a particular Quinary's WTI and subsequently dividing this value by the accumulated streamflows for the same Quinary. Maximum mixed water temperature is an important ecological attribute and can be applied in climate change studies to determine the differences in maximum mixed water temperature between different GCM time periods as a ratio, or as a $^{\circ}\text{C}$ difference in water temperature.

The results of the spatial modelling for the water temperature related indicators are given and interpreted in **Chapter 13**.

10.7 Time Series Analyses

Time series analyses were performed on water temperature related indicators at 15 selected Quinary Catchments located in the Thukela Catchment. These time series analyses use the same datasets and climate scenarios outlined in **Sections 10.2-10.6**.

The time series analyses use two methods to describe how each water temperature related indicator may vary over time, *viz.*

- How values of the indicator may vary within a single Quinary catchment when comparing the three ECHAM5 climate scenarios (i.e. a temporal analysis), with the hypothesis being that in future climates the temperatures are increasing and streamflows are changing; and
- How values of the indicator may vary between the three Quinaries making up a Quaternary Catchment when using a single climate scenario (i.e. a spatial analysis), with the hypothesis being that Quinaries within a Quaternary are altitude dependent and that this should therefore result in changes in temperature, rainfall, runoff and thus water temperature patterns between the upper, middle and lower Quinaries.

The results and interpretations of the time series analyses for the Thukela Catchment are provided in **Chapter 14**.

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CHAPTER 11 RESULTS 1: EVALUATION OF POTENTIAL CHANGES IN HYDROLOGICALLY RELEVANT STATISTICS OF RAINFALL IN SOUTHERN AFRICA UNDER CONDITIONS OF CLIMATE CHANGE, USING GRIDDED REGIONAL CLIMATE CHANGE SCENARIOS

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11.1 Introduction and Objectives

A focus on potential impacts of climate change on the water sector of southern Africa (i.e. the Republic of South Africa together with Lesotho and Swaziland) was triggered by a series of activities and events in the first few years of the new millennium which included the World Summit on Sustainable Development, the Intergovernmental Panel on Climate Change (IPCC) reports in 2001 and 2007, the third and fourth World Water Fora, as well as active South African participation in, *inter alia*, the International Geosphere-Biosphere Programme and the International Dialogue on Water and Climate, among others. Additionally, there was the realisation that perturbations in climate parameters, particularly of rainfall, were amplified by the hydrological system (c.f. **Chapter 8**) and that if climate changes were to manifest themselves in the manner which international science was projecting, it would add a further layer of concern to the management of southern Africa's already high risk and stressed water sector, with potential implications to the entire region's socio-economic well-being, but particularly that of the poor.

In this chapter results from a case study conducted at the scale of southern Africa (defined here as the contiguous area making up the RSA, Lesotho and Swaziland) are presented, based on the methodologies outlined in **Chapter 9**. An evaluation is made of future versus present changes in hydrologically relevant rainfall statistics derived from a number of climate scenarios. Apart from determining where convergence exists amongst the different scenarios, the analysis of trends also focuses on exploring the likely implications for the southern African water sector.

11.2 Methodology

Details of the methodology and approaches used in this case study have been given in **Sections 9.2.1** and **9.2.2** of this report and are therefore only summarised here. The GCMs used to develop the climate scenarios used in this case study were empirically downscaled to a quarter degree resolution spatial grid for southern Africa (Hewitson *et al.*, 2005) and included three from the IPCC Third Assessment Report (IPCC, 2001), and three from the World Climate Research Programme's Coupled Model Intercomparison Project Phase 3 (CMIP3) multi-model dataset used in the IPCC Fourth Assessment Report (IPCC, 2007), i.e. the CMIP 3 archive. The GCMs, details of which are given in **Table 9.1** in **Chapter 9**, are:

- CSIRO,
- ECHAM, and
- HadAM,

Which were employed in the IPCC's Third Assessment Report (TAR), and

- GFDL,
- MIROC, and
- MRI-CGCM,

which were employed in the Fourth Assessment Report (AR4). The future global climate scenarios were simulated based on the A2 emissions scenario (IPCC, 2001) which assumes that efforts to reduce global emissions this century are relatively ineffective. Regional scenarios were developed for present, intermediate future and more distant future climates represented by the following time periods:

- present climate: $\pm$ 1960-1990 for both AR4 and TAR models,
- intermediate future climate: $\pm$ 2046-2065 for AR4 models only,
- distant future climate: $\pm$ 2081-2100 for AR4 models, and
 $\pm$ 2070-2100 for TAR models.

All the above regional scenarios included a daily time series of rainfall for each climatic period and the $\pm$ denotes that the respective scenarios derived from the different GCMs were not for identical time periods.

In this case study emphasis is placed on assessing the possible changes in hydrologically relevant rainfall statistics under the intermediate future rather than the more distant future climate. The reason for this is that the distant future climate is more dependent on the emissions scenario adopted than the intermediate one, and is thus subject to greater uncertainty. It is also easier for most individuals to relate to a time period that commences $\pm$ 40 years from now, rather than a period that commences $\pm$ 70 years from now.

The assessment of possible changes was performed at a scale suitable for hydrological modelling in the region, viz. the Quaternary Catchment (QC) scale. In order to represent the regional climate scenarios at QC scale, pixels were selected from the 0.25° regional scenario grids to represent each of the 1 946 QCs in southern Africa using the steps outlined in **Section 9.2.2** and illustrated in **Figures 9.1** and **9.2**.

11.3 Hydrologically Relevant Rainfall Statistics

The hydrologically relevant statistics of rainfall assessed in this case study focused on characterising the annual means and variances of the rainfall scenarios, as well as the exceedence of critical daily rainfall thresholds. The exceedence of daily rainfall thresholds was represented by determining the total number of days in the relevant daily time series on which rainfall either equalled or exceeded certain defined threshold amounts. This would give an indication of whether individual rainfall events are likely to be larger or smaller in future, than at present. It is important to consider individual rainfall events, as these trigger key hydrological responses such as stormflow and sediment generation. The statistics that were analysed were:

- mean annual precipitation (MAP), the
- coefficient of variation (CV) of annual precipitation, the
- total number of days in the time series with no rainfall, the
- total number of days in the time series with > 5 mm of rainfall, the
- total number of days in the time series with > 10 mm of rainfall, and
- total number of days in the time series with > 20 mm of rainfall.

Considering days with no rainfall vs. days with rainfall has significance in terms of general antecedent wetness. The threshold of 10 mm on a given day was considered in the analysis since this is often viewed as a threshold for stormflow to occur, or for farmers not being able to implement mechanical field operations. The threshold of 5 mm was selected as an intermediate threshold between zero and

10 mm. The threshold of 20 mm was selected to represent heavier rainfall events associated with higher stormflows and the generation of sediment yield.

In order to make a fair comparison, the number of years of data considered in statistical calculations was kept the same when comparing the statistics from the intermediate future and distant future climates to the present climate. Thus, for the regional scenarios derived from the AR4 GCMs, only 20 of the 30 years of available data in the present climate scenario were used in calculating statistics so as to be comparable with the 20 years of data available for the intermediate and distant future climates. For this case study the last 20 years of data from the 30 year present climate series were considered since the selection of this period resulted in a more equal spacing of the different climates over time.

11.4 Results

The projected changes in hydrologically relevant rainfall statistics are presented as maps of the ratio of the intermediate future (or distant future, as the case may be) climate statistic to that of the present climate statistic. Thus, a ratio value > 1 indicates an increase in that statistic in a future climate (mapped in shades of green and blue), while a ratio value < 1 indicates a decrease (mapped in shades of red and brown). A ratio in the range 0.95-1.05 was considered to be a negligible change and was indicated in the maps as unshaded areas of 'No Change'.

11.4.1 Potential changes in hydrologically relevant rainfall statistics under an intermediate future climate

The potential changes in hydrologically relevant rainfall statistics under an intermediate (mid-21st century) climate are presented in **Figure 11.1** for a) mean annual precipitation, b) CV of annual precipitation, c) total number of days with no rainfall, d) total number of days with rainfall exceeding 5 mm per day, e) total number of days with rainfall exceeding 10 mm per day, and f) total days number of days with rainfall exceeding 20 mm per day. The changes in **Figure 11.1** are all based on the regional climate scenarios derived from AR4 GCMs, since there were no regional climate scenarios derived from TAR GCMs for the intermediate future climate.

In **Figure 11.1** (left hand maps, also designated 'a'), the regional climate scenarios derived from three AR4 GCMs consistently project a reduction in MAP along the west coast and adjacent interior of the region. This is bordered by a transition zone in the western interior where there are catchments experiencing little or no change in MAP. For the remainder of the region, a wetting trend of increasing MAP is evident. The MIROC scenario presents the driest scenario of the three for the west at 60-80% of present MAP, while the MRI-CGCM presents the wettest trend of the three GCMs in the east with a projected increase in MAP of 20-40%. The GFDL scenario appears to be a 'middle-of-the-range' scenario.

In **Figure 11.1** (right hand maps, 'b'), there are no obvious patterns in the changes in inter-annual variability of rainfall in the various regional scenarios, although there is a slight tendency towards higher year-on-year variability where MAP was projected to decrease, i.e. along the west coast and adjacent interior.

With respect to changes in the distribution of daily rainfall amounts, all three scenarios project an increase in the number of rainless days in a small area in the southwestern corner of the Western Cape province, and a decrease in the number of days in the eastern half of the region (**Figure 11.2**, left hand maps, also designated 'c'), with the remainder of the region displaying no evident change in

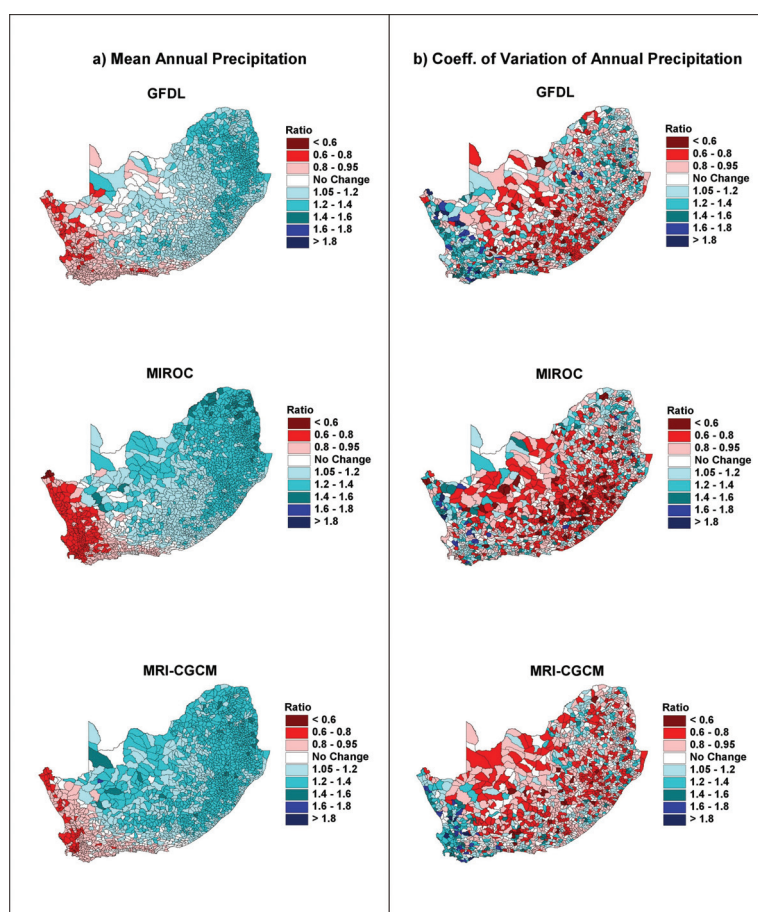


Figure 11.1 Ratios of intermediate future to present climate rainfall statistics: a) mean annual precipitation and b) coefficient of variation of annual rainfall

the number of rainless days. In the map of the number of days with more than 5 mm of rainfall (**Figure 11.2** right hand maps, 'd'), all scenarios project a decrease in the number of days in the west, while there is an increase in the central and eastern parts, and a transition zone in the western interior. **Figure 11.2d** displays similar patterns and magnitudes of change to the map for MAP (**Figure 11.1a**).

In the maps of the number of days with more than 10 and 20 mm of rainfall (**Figure 11.3** left hand and right hand maps, respectively), the scenarios project the same trend for the east of the region as the 5 mm threshold map (**Figure 11.2**), with the increases becoming progressively more marked for the bigger events. The decreases in the number of days in the west of the region become less evident, with the transition zone (very mixed signal) in the western interior now effectively extending through to the west coast.

11.4.2 Potential changes in hydrologically relevant rainfall statistics under a distant future climate

Since more emphasis was placed in this study on comparing the intermediate future climate to the present climate, only potential changes in *mean annual precipitation* (MAP) under the distant future climate scenarios are presented here in order to give a general indication of projected changes in rainfall over the remainder of the century. These projected changes are presented in **Figure 11.4** for the regional climate scenarios derived from both AR4 and TAR GCMs.

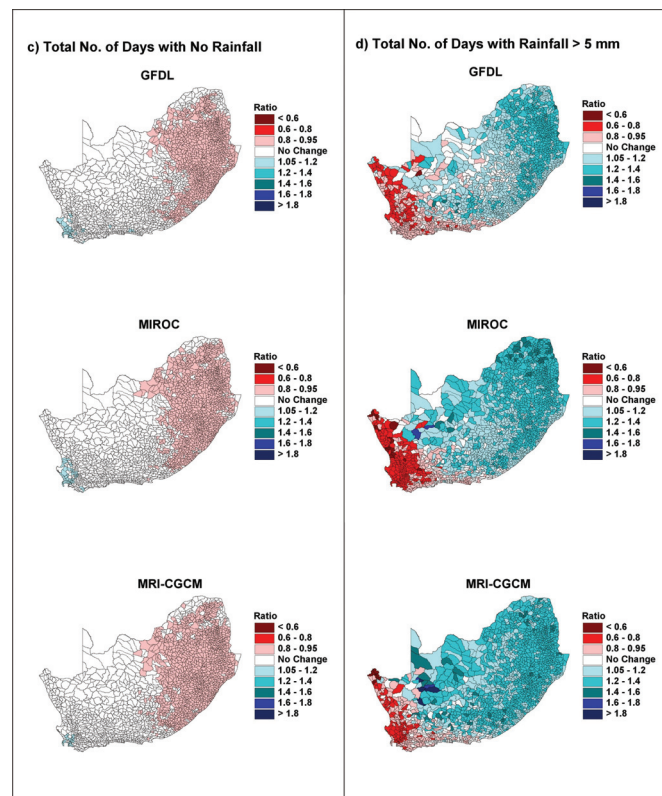


Figure 11.2 Ratios of intermediate future to present climate rainfall statistics: c) total number of days with no rainfall and d) total number of days with rainfall > 5 mm

For the regional climate scenarios derived from the AR4 GCMs, the trends in MAP evident under the intermediate future climate become more pronounced for the distant future climate. For the regional climate scenarios derived from TAR GCMs, there is less consistency in the trends in MAP under the distant future climate than there is in those scenarios derived from AR4 GCMs. The change in MAP according to the ECHAM derived scenarios shows wetting over almost the entire region, except along the west coast. Some of the wetting is extremely marked, with certain areas projected to receive 80% more rainfall in the distant future than at present. The HadAM derived scenario shows the largest transition zone between eastern and western areas of the region, with the zone extending further eastwards than any of the other five models and also showing more catchments with no change in MAP. The CSIRO derived scenario shows a strong wetting trend in the western interior, whereas other models show a mixed signal transition zone there. The scenarios derived from the TAR GCMs all show drying in the west of the region, but this is generally less in terms of area and severity than the more recent scenarios derived from the AR4 GCMs.

11.5 Discussion

The analysis of statistical trends in **Figures 11.3** and **11.4** has shown that there is more consistency in the trends for scenarios derived from AR4 GCMs, as opposed to older (~ year 2000) TAR GCMs. The main differences between the scenarios derived from TAR GCMs (in terms of trends in MAP for the distant future climate) include the following:

- the strong wetting in the western interior according to the CSIRO derived scenarios,
- the relatively large area in the western and central interior showing no change according to the HadAM derived scenarios, and

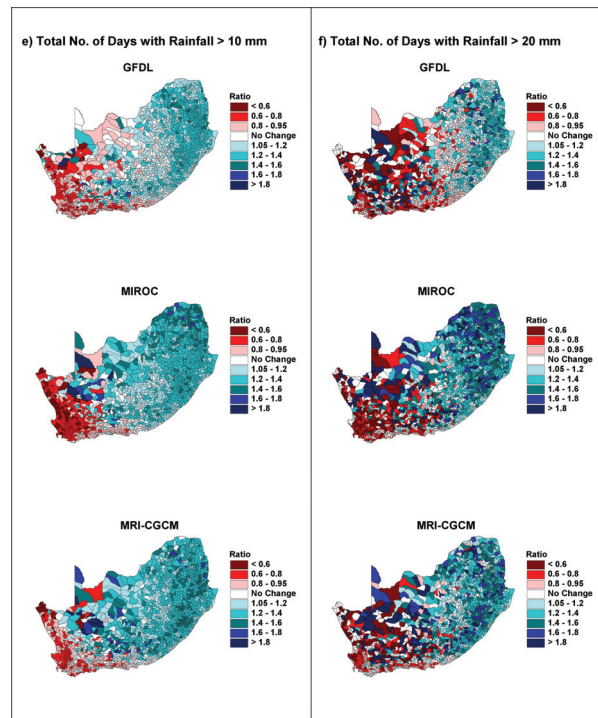


Figure 11.3 Ratios of intermediate future to present climate rainfall statistics: e) total number of days with rain

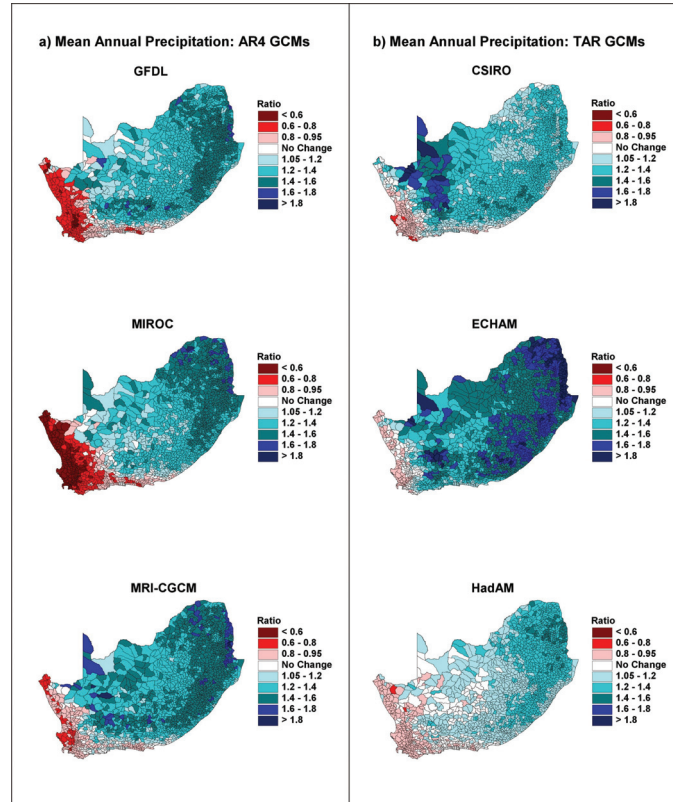


Figure 11.4 Ratios of distant future to present mean annual precipitation according to regional climate scenarios derived from a) AR4 and b) TAR general circulation models

- the very marked increase in MAP (of more than 80%) projected for the extreme eastern parts of the region and parts of the Limpopo Province of South Africa by the ECHAM derived scenarios.

Given the greater consistency in trends for the AR4 derived scenarios used in the above case study, it is proposed that these scenarios should be applied in hydrological models when explicitly assessing the impact of climate change on hydrological responses.

According to all of the scenarios evaluated in the study, more rainfall is projected for the east of the region. This rainfall comes in the form of more raindays (**Figure 11.1**) and more days with bigger rainfalls (**Figure 11.3**). If these scenarios are correct, then the combination of wetter antecedent conditions and larger rainfall events would result in more runoff being generated and this would have implications for, *inter alia*, filling of dams. There would also be implications for water quality, and in particular, sediment related water quality which affects, *inter alia*, water treatment, dam siltation and aquatic ecosystems. The above trends are projected to extend to end of the century. It is unclear at this stage whether the projected change will be more rapid in the former or latter half of the century.

According to all of the scenarios evaluated, less rainfall is projected along the west coast and the adjacent interior, with the possibility of a slight increase in inter-annual variability. If correct, these trends would result in a decrease in flows and an increase in flow variability, since changes in precipitation are amplified in the hydrological cycle. It is likely that the mixed signal in the temporal distribution of rainfall will also be reflected in the incidence of stormflow events in this area.

It is significant that the regional climate scenarios evaluated in this chapter project much larger increases in rainfall in the east of the region than the scenarios of Engelbrecht's (2005) from the C-CAM GCM, as evaluated by Schulze *et al.* (2005). The scenarios evaluated in this chapter, which were developed over a longer period of time, were produced at a spatial resolution four times finer than the 2005 study and were also derived from a number of climate models instead of just a single one. The unanimous trend of wetting in the east projected by the scenarios is of significance, and is in agreement with the multi-model mean as projected in the IPCC AR4 for summer.

In contrast to the east of the region, where disparities in projected changes exist between the C-CAM climate scenarios in Engelbrecht (2005) and the scenarios evaluated in this paper, both sources project relatively strong drying along the west coast and adjacent interior. The C-CAM future climate scenarios, like the scenarios evaluated in this paper, were simulated assuming the SRES A2 emissions scenario.

11.6 Recommendations for Further Research

It is recommended that the following be investigated in future research:

- the rate of expected change in the first half of this century versus that in the second half of the century
- possible shifts in the seasonal timing of rainfall
- projected changes in extreme rainfall events
- the impact of projected climate change on other climatic variables, e.g. temperature and potential evaporation
- the explicit assessment of the impacts of projected climate change on hydrological responses through the application of climate scenarios in a hydrological model

- the application of alternative emissions scenarios in climate scenario development to define the full envelope of possible change

11.7 Conclusions

The regional scenarios of climate change evaluated in this section facilitate studies of the impact of climate change on water resources to be conducted at a finer spatial scale and with a greater degree of confidence (stemming from the availability of multiple scenarios), than has previously been the case. As convergence becomes apparent, there is now an arguable basis for developing appropriate response strategies for incorporation into adaptation policy. Perhaps one of the greatest challenges in this regard is now to explore the issues of uncertainty and probability in order to develop a more rigorous basis to enable proactive responses.

11.8 Acknowledgements

The modelling groups, the Program for Climate Model Diagnosis and Inter-comparison (PCMDI) and the World Climate Research Programme's (WCRP's) Working Group on Coupled Modelling (WGCM) are thanked for their roles in making available the WCRP CMIP3 multi-model dataset. Support of this dataset is provided by the Office of Science, US Department of Energy.

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CHAPTER 12 RESULTS 2: CHANGES IN SELECTED ECO-HYDROLOGICAL FLOW INDICATORS OVER SOUTHERN AFRICA UNDER REGIMES OF CLIMATE CHANGE AS PROJECTED BY THE ECHAM5/MPI-OM GENERAL CIRCULATION MODEL

K.R. Barichievy, R.E. Schulze and R.P. Kunz

12.1 Background

The *ACRU* model was used to simulate the eco-hydrological responses from the 5 838 hydrologically interlinked and cascading Quinary Catchments which constitute the southern African study region of the RSA, Lesotho and Swaziland. The *ACRU* model was run with 20 years of daily climate records using

- Baseline (i.e. historically observed) climate (1971-1990),
- Present climate from the ECHAM5/MPI-OM Global Climate Model, hereafter referred to as ECHAM5 (1971-1990), and
- Intermediate future climate (2046-2065) from ECHAM5, and a more
- Distant future climate (2081-2100) from ECHAM5.

Of the downscaled daily output from the five GCMs received for this project from the Climate Systems Analysis Group at the University of Cape Town (cf. **Chapter 9**) only the output from the ECHAM5/MPI-OM GCM had gone through all the computationally exacting and highly time consuming configuration procedures needed for hydrological climate change applications with the *ACRU* model towards the end of 2008 when the eco-hydrological analyses were performed. ECHAM5 was thus the only GCM the required output of which was available for this research. ECHAM5 was selected because of the five GCMs received it represents relatively “middle of the road” future rainfall scenarios for southern Africa, with some of the other GCMs projecting drier and others wetter future rainfall conditions.

The limitations of using output from a single GCM for impact studies are well documented (e.g. Hewitson *et al.*, 2005; Schulze *et al.*, 2007; IPCC, 2007) and are well appreciated by the project team. However, this report has its focus on development of techniques rather than on the certainty or uncertainty of results.

Note that on all maps which follow the term “Intermediate” refers to the intermediate future climate scenario while “Future” refers to the more distant future climate scenario.

12.2 Magnitudes of Flow Events

12.2.1 Setting the scene

Both individual subcatchment runoff and accumulated streamflows were used to describe the magnitudes of flows and changes to these flows with projected climate change. Maps for southern Africa were generated from the output of the *ACRU* model when using daily values from the climate scenarios listed above as input. In order to keep the array of maps to a manageable number, only the annual values and those of four selected cardinal months, representing the four major seasons, were analysed. In regard to the selected cardinal months, January represents conditions in summer, April in autumn, July in winter and October represents the spring months. The annual results may be utilised to illustrate overall trends for each scenario while the monthly time scale provides a more

focussed representation in order to determine intra-annual, i.e. seasonal, differences. The spatial analyses for the magnitudes of flow events comprises a ratio comparison, at a mean annual and at a mean monthly level, between the three ECHAM5 climate scenarios, specifically ratios of the intermediate future to present and those of the more distant future to present climate scenarios, in order to determine how a particular indicator is projected to be changing from one climate scenario to the next in the future. A map for each selected flow indicator was also generated for historical climatic conditions as a baseline, or reference, to display spatial patterns of the indicators under current climatic conditions. A spatial analysis of the inter-annual variability of the magnitude indicators was performed for both individual subcatchment runoff and accumulated streamflows using the Coefficient of Dispersion (CoD, described in **Chapter 3**). This was done to gain information on how the magnitude of flows may vary from year to year and also change under projected future climatic conditions.

12.2.2 Average annual flow projections for individual subcatchment runoff

Simulated runoff from individual subcatchments, in this case Quinary Catchments, is a standard output from the *ACRU* model and is defined as the sum of stormflows and baseflows from only the subcatchment in question, excluding any contributions from upstream catchments (Schulze, 1995). The *ACRU* model outputs runoff in millimetre (mm) equivalents per day and this is subsequently converted to a flow rate ($\text{m}^3 \cdot \text{s}^{-1}$) using the Quinary Catchment's area. An analysis of individual subcatchment runoff is important because adding accumulated streamflows from upstream can mask the runoff characteristics of the individual subcatchment in question.

Figure 12.1 displays the mean annual runoff from individual subcatchments for southern Africa, the CoD of subcatchment runoff as well as the ratio comparisons for the three ECHAM5 climate scenarios for both these indicators. The historical baseline map for subcatchment runoff (**Figure 12.1** top left) shows a general decrease in runoff in an east to west direction. The Quinary Catchments in the Northern Cape province display unusually high runoff for such a semi-arid part of southern Africa. The cause of this apparent anomaly is that the unit used to measure flow magnitude, viz. $\text{m}^3 \cdot \text{s}^{-1}$, is a function of catchment area and the areas of these Quinaries are among the largest in the study region - hence the relatively large magnitudes of flow there.

The CoD of subcatchment runoff for the historical baseline scenario (**Figure 12.1** top right) indicates the wetter eastern regions of southern Africa to experience less inter-annual variability of subcatchment runoff than the drier Northern Cape, which typically displays high CoD values of between 2 and 5 as a result of experiencing erratic year to year rainfall. The ratio map for mean annual runoff derived from intermediate future to present projected climates (**Figure 12.1** middle left) indicates that a large majority of the Quinary Catchments in the eastern parts in southern Africa are likely to experience an increase in runoff according to the ECHAM5 GCM. A band of Quinaries running roughly from the Limpopo province through to the Eastern Cape indicates a decrease in subcatchment runoff in the intermediate future. This trend of increasing runoff in the eastern parts of southern Africa continues and expands as well as intensifies when comparing the runoff ratio from the distant future to present ECHAM5 climate scenarios (**Figure 12.1** bottom left), while the band of Quinaries which is projected to experience a decrease in subcatchment runoff shifts westwards to now cover the southwestern parts of the Western Cape. The ratio maps for the CoD of subcatchment runoff under projected future climates (**Figure 12.1** middle right and bottom right) do not display clear overall trends; however, most Quinaries do seem to indicate a decrease in CoD for both the intermediate and more distant future climate scenarios.

12.2.3 Average annual flow projections for accumulated streamflows

Accumulated streamflow is a standard output from the *ACRU* model and is defined as the total summed streamflow from a (sub)catchment, but which also includes any contributions from upstream catchments flowing into that (sub)catchment (Schulze, 1995). The *ACRU* model outputs this variable in millimetre (mm) equivalents and it is subsequently converted to cubic metres (m³) using the total (sub)catchment area. **Figure 12.2** displays the mean annual accumulated streamflows per Quinary Catchment in southern Africa, for the climate scenarios described in **Section 12.1**. The historical baseline map (**Figure 12.2** top left) clearly shows streamflow accumulation in the major river systems (e.g. the Orange, Vaal and Thukela), indicated by the darker blue colours. The CoD of accumulated streamflows for the historical baseline scenario (**Figure 12.2** top right) indicates that the eastern regions of southern Africa are likely to experience less flow variability compared to the Quinaries located in the drier Northern Cape Province which, as in the case of subcatchment runoff (**Section 12.2.2**), typically display a CoD of between 2 and 5.

Figure 12.2 (middle left and bottom left) also displays the ratio comparisons of mean annual accumulated streamflows between the ECHAM 5 climate scenarios. Both maps indicate an increase in accumulated streamflows in eastern parts of southern Africa under projected future climate conditions. The ratio map of distant future to present ECHAM5 climates (**Figure 12.2** bottom left) displays the greatest change in accumulated streamflows, with most Quinaries on the east coast showing an increase by a factor of between 2 and 5 compared to that simulated from the present ECHAM5 climate scenario. As in the case of subcatchment runoff, there is a band of Quinaries running roughly from Limpopo province through to the Eastern Cape province which indicates a decrease in accumulated streamflows (**Figure 12.2** middle left). This trend of increasing streamflow continues when assessing the ratios generated from the distant future to present ECHAM5 climate scenarios (**Figure 12.2** bottom right), and again the band of Quinaries which experiences a decrease in accumulated streamflows shifts westwards and now covers the southwestern parts of the Western Cape. The ratio maps for the CoD of accumulated flows under projected future climates (**Figure 12.2** middle right and bottom right) do not display distinctive trends. However, most Quinaries do seem to indicate a decrease in CoD in both the intermediate and more distant future scenarios, particularly on the Eastern Cape and KwaZulu-Natal coasts.

12.2.4 Average flow projections for individual subcatchment runoff in selected months

An analysis of subcatchment runoff projections for the four cardinal months selected was performed at Quinary Catchments scale for southern Africa (**Figures 12.3-12.5**). A spatial analysis of subcatchment runoff for present baseline climate (1970-1990) and a ratio comparison between the three ECHAM5 climate scenarios was performed for the months of January, April, July and October. A CoD analysis of subcatchment runoff was also performed, however only for the representative summer and winter months, viz. January and July.

A comparison of the historical baseline maps for the four cardinal months reveals certain trends which are not shown in the annual analysis of subcatchment runoff (cf. **Section 12.2.2**). The January baseline map for subcatchment runoff (**Figure 12.3** top left) displays the greatest amount of runoff of the four months, especially in the eastern parts of the study region which experiences a summer rainfall regime. Conversely, the Western Cape displays virtually no runoff for the month of January. This regional trend reverses for the month of July, when the Western Cape receives its winter rainfall (**Figure 12.4** top left) and thus generates more runoff than the eastern parts of southern Africa. The historical baseline climate maps for the months of April and October (**Figure 12.5** top left and right)

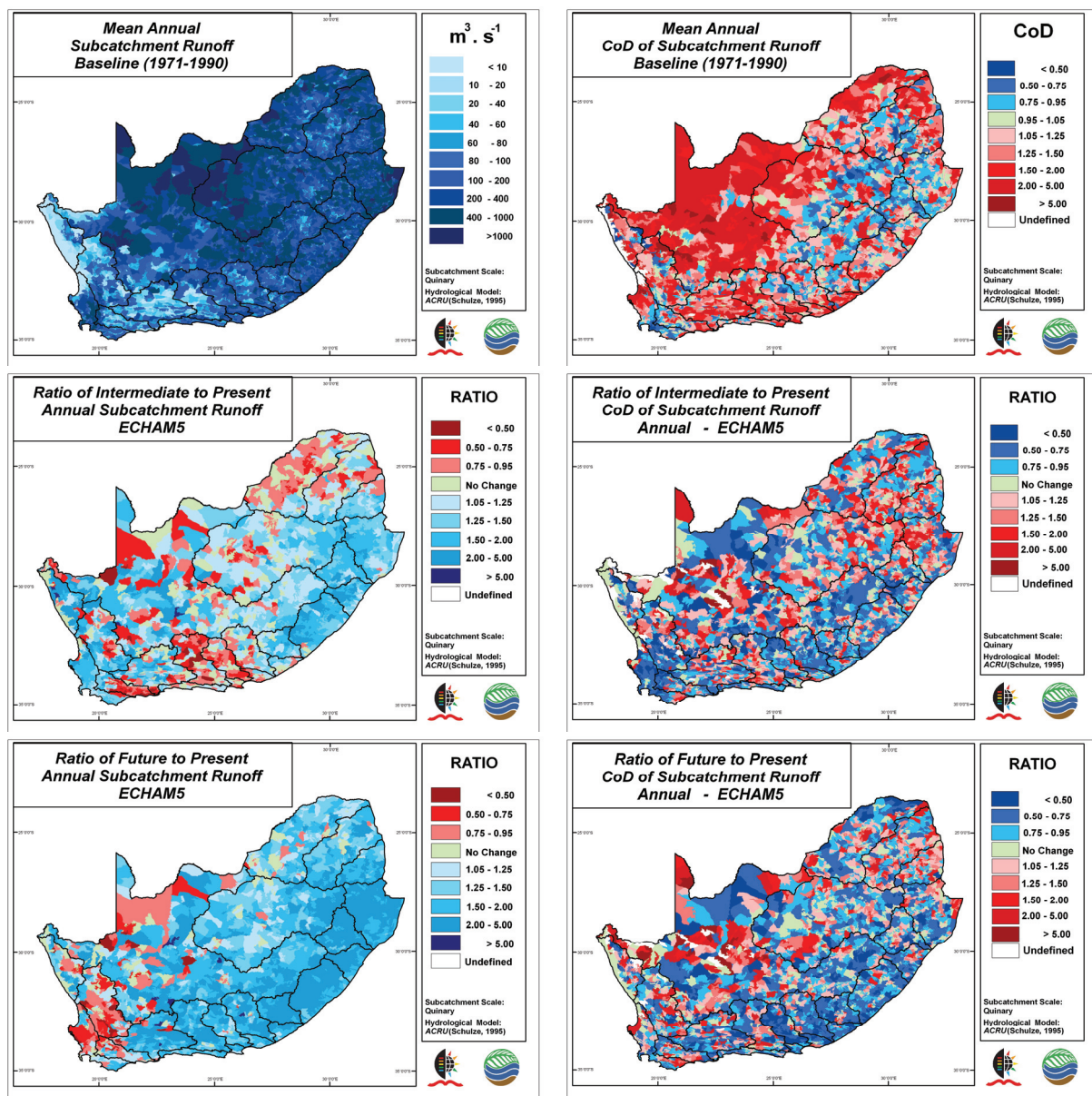


Figure 12.1 Mean annual individual subcatchment runoff ($m^3 \cdot s^{-1}$) under baseline climatic conditions, as well as ratios of the intermediate future to present and more distant future to present subcatchment runoff derived with the ACRU model from ECHAM5 climate input (left hand maps), together with their respective Coefficients of Dispersion (right hand maps)

show similar trends with respect to subcatchment runoff, but with April experiencing more runoff than October in the Free State. The high values for subcatchment runoff recorded from the large Quinary Catchments in the Northern Cape for January and April is hypothesised to be the result of using $m^3 \cdot s^{-1}$ as the unit of flow rather than mm equivalents (cf. **Section 12.3**).

A ratio analysis of individual subcatchment runoff generated from the three ECHAM5 scenarios was also performed for the four cardinal months. The ratio analysis for January illustrates a distinct band of decreasing subcatchment runoff trending from the northeastern tip of South Africa to the Eastern Cape province for the intermediate future to present ratio (**Figure 12.3** middle left), with most Quinaries in this band experiencing a decrease in subcatchment runoff of between 5% and 50%. This

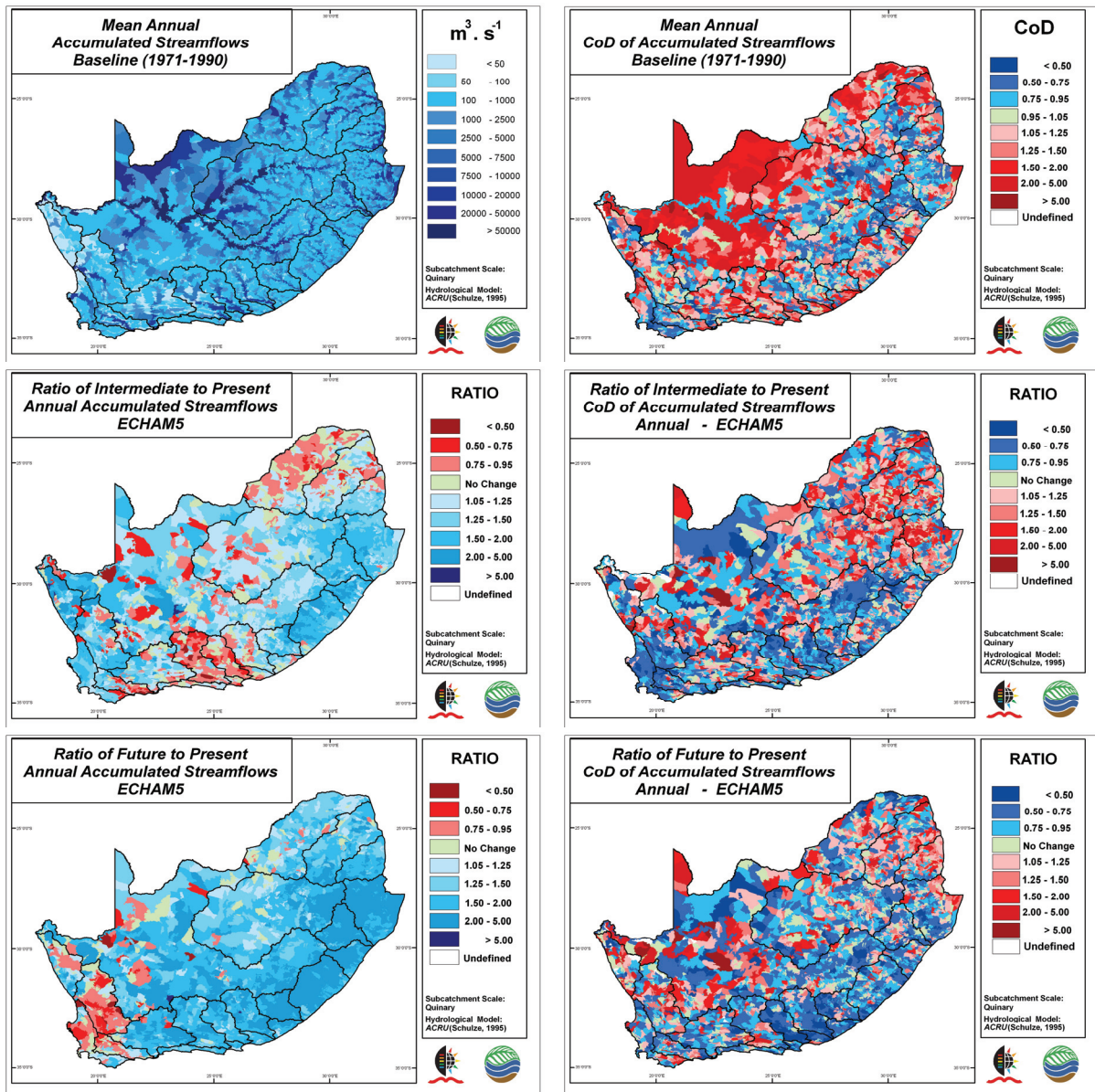


Figure 12.2 Mean annual accumulated streamflows (m³.s⁻¹) under baseline climatic conditions, as well as ratios of the intermediate future to present and more distant future to present accumulated streamflows derived with the ACRU model from ECHAM5 climate input (left hand maps), together with their respective Coefficients of Dispersion (right hand maps)

band then shifts westward in the distant future to present ratio analysis (**Figure 12.4** bottom left). The eastern seaboard of southern Africa is projected to experience an increase in subcatchment runoff in both the intermediate and more distant future climate scenarios generated by the ECHAM5 GCM. The ratio analysis for July indicates that most of the region can expect an increase in subcatchment runoff in the intermediate future (**Figure 12.5** middle left). This wetting trend is projected to become stronger under the more distant future climatic conditions (**Figure 12.5** bottom left). April and October, the transitional months, show similar results for both ratio analyses (**Figure 12.5** middle and bottom), with October displaying a stronger wetting signal. For both months a general wetting is projected along the east coast of southern Africa for both scenarios, but especially for the future to present analysis, which shows that most Quinaries in this region are likely to experience an increase

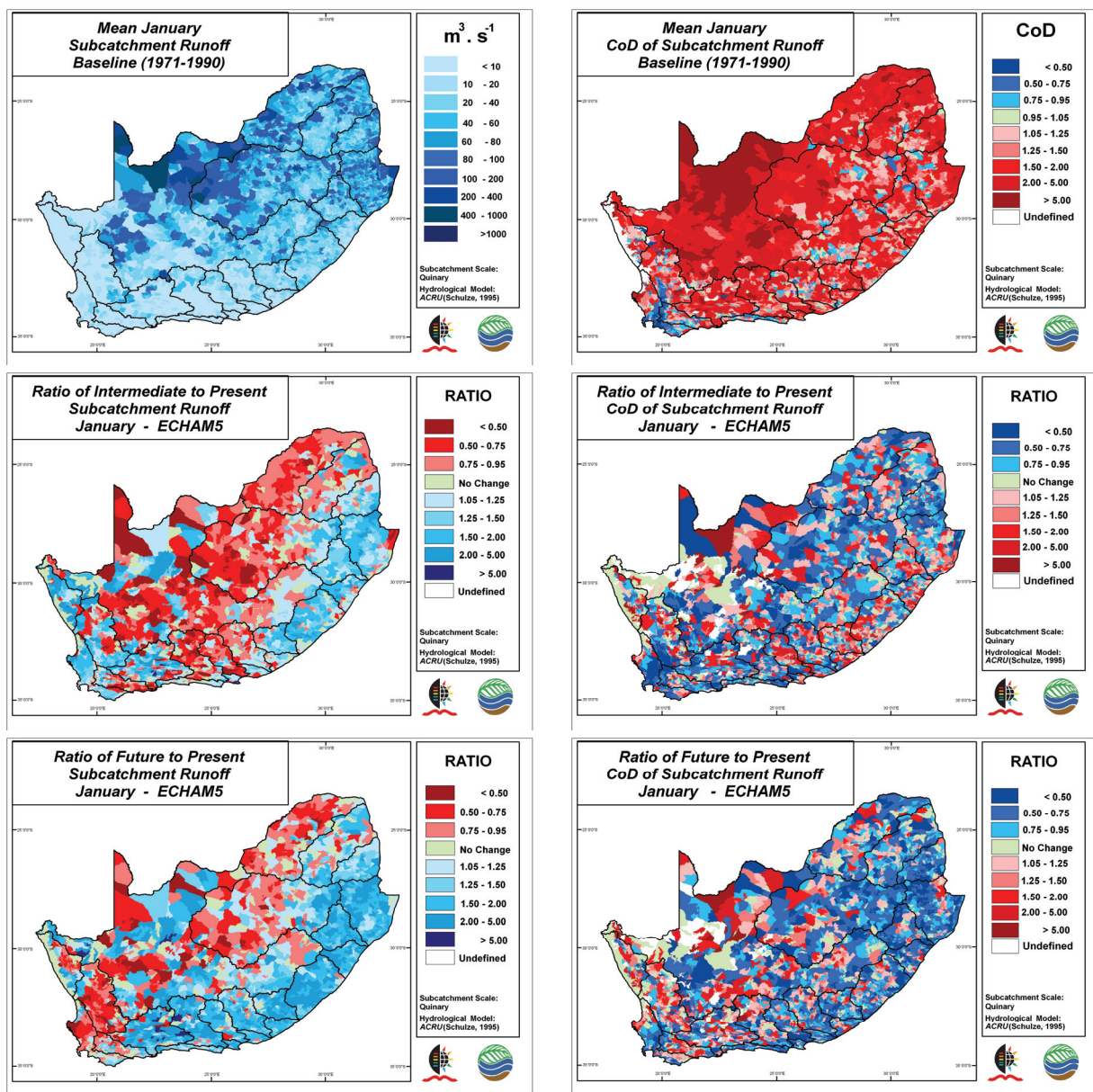


Figure 12.3 Mean January individual subcatchment runoff ($\text{m}^3 \cdot \text{s}^{-1}$) under baseline climatic conditions, as well as ratios of the intermediate future to present and more distant future to present subcatchment runoff derived with the ACRU model from ECHAM5 climate input (left hand maps), together with their respective Coefficients of Dispersion (right hand maps)

in runoff by a factor of between 2 and 5 based on the ECHAM5 GCM. Both these months also project a decrease in runoff in the Western Cape in the more distant future compared to the present climate scenario.

A monthly analysis for the CoD of subcatchment runoff was performed for the months of January and July to determine if any differences in spatial patterns of inter-annual runoff were evident. Both January and July exhibit a high CoD for much of the region under present baseline climatic conditions (**Figures 12.3** and **12.4** top left), especially in the Northern Cape province, implying that year to year

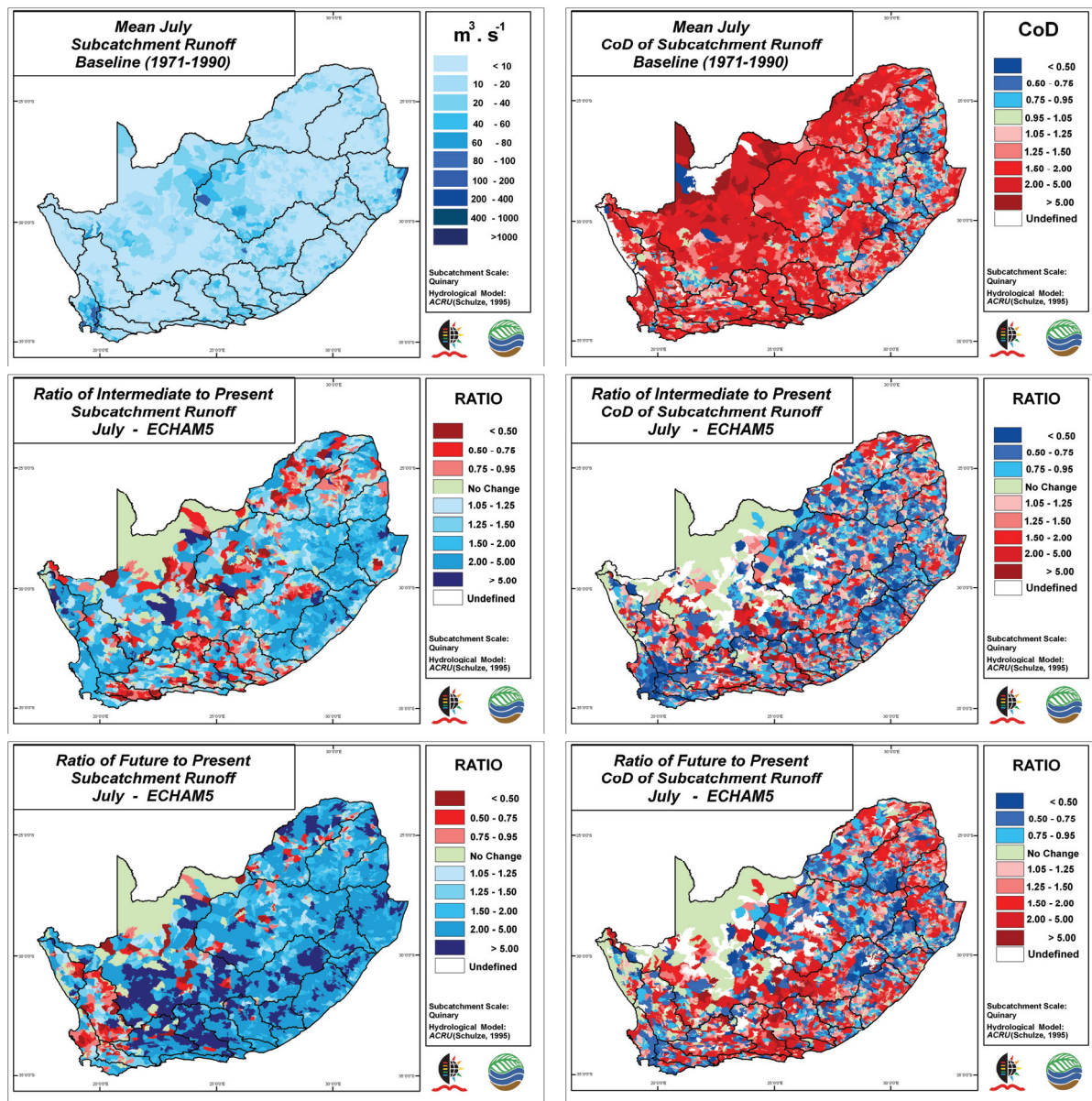


Figure 12.4 Mean July individual subcatchment runoff ($m^3 \cdot s^{-1}$) under baseline climatic conditions, as well as ratios of the intermediate future to present and more distant future to present subcatchment runoff derived with the ACRU model from ECHAM5 climate input (left hand maps), together with their respective Coefficients of Dispersion (right hand maps)

runoff values are highly variable for these months. January displays lower CoD values, of between 0.5 and 0.75 for the Western Cape which is then in its dry season, while July shows lower CoD for eastern parts of southern Africa when that region is in its dry season. The January ratio analysis for the CoD of subcatchment runoff does not reveal any clear regional trends, except that there seems to be an overall decrease in CoD, particularly for the distant future to present ratio analysis (**Figure 12.3** bottom right). Like January, July does not exhibit any clear trends in changes of CoD, except that the more arid regions are projected not to experience any significant change in the inter-annual variability of subcatchment runoff under future climatic conditions, owing to the lack of runoff in the dry season.

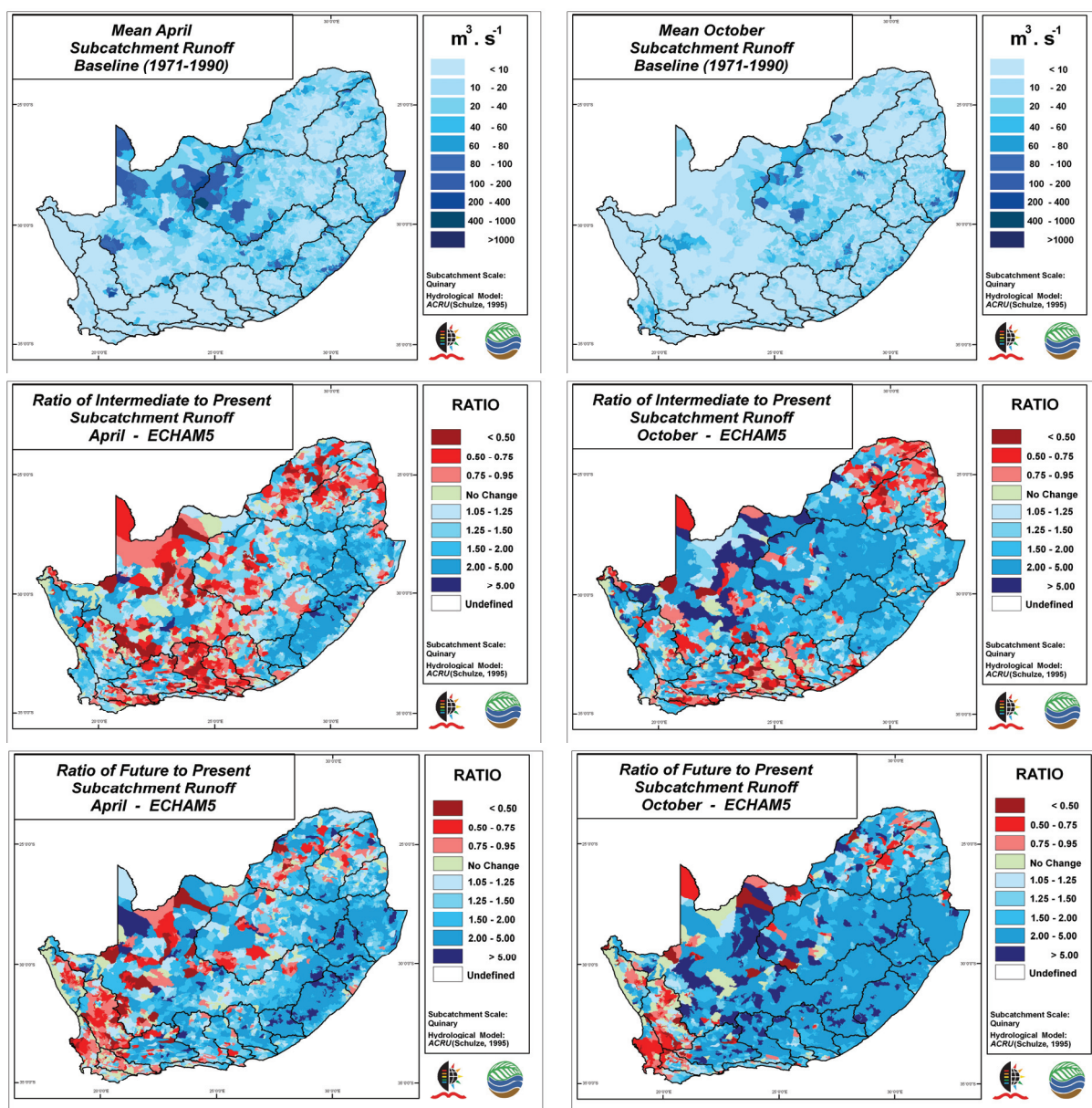


Figure 12.5 Mean April and October individual subcatchment runoff ($\text{m}^3 \cdot \text{s}^{-1}$) under baseline climatic conditions (top maps), as well as ratios of the intermediate future to present (middle row) and more distant future to present subcatchment runoff (bottom row) derived with the ACRU model from ECHAM5 climate input

12.2.5 Average flow projections for accumulated streamflows in selected months

An analysis of seasonal (i.e. intra-annual) changes in accumulated streamflow projections for selected cardinal months (**Figures 12.6-12.9**) reveals that accumulated streamflows fluctuate quite considerably throughout the year. A spatial analysis of accumulated streamflows for present baseline climate (1971-1990) and a ratio comparison between the three ECHAM5 climate scenarios was performed for the months of January, April, July and October. As with subcatchment runoff (cf. **Section 12.2.3**), a CoD analysis of accumulated streamflows was performed for January and July.

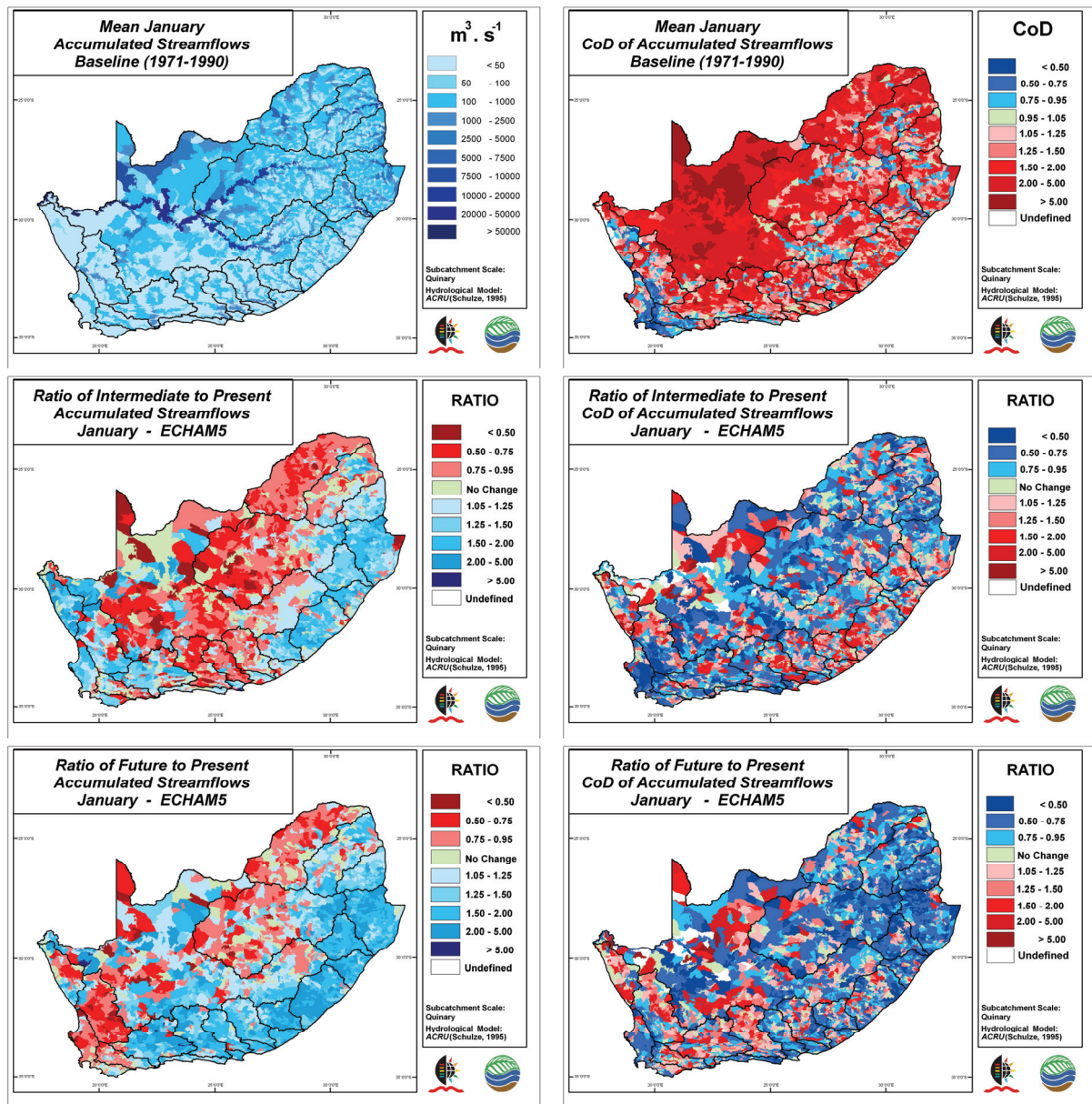


Figure 12.6 Mean January accumulated streamflows ($\text{m}^3 \cdot \text{s}^{-1}$) under baseline climatic conditions, as well as ratios of the intermediate future to present and more distant future to present accumulated streamflows derived with the ACRU model from ECHAM5 climate input (left hand maps), together with their respective Coefficients of Dispersion (right hand maps)

Similarly to the annual analyses (**Section 12.2.2**), the monthly baseline maps for accumulated streamflows (**Figures 12.6-12.9**) clearly illustrate the streamflow accumulations in the major river systems (e.g. the Orange, Vaal and Thukela), indicated by the darker shades of blue. The January baseline map for accumulated streamflows (**Figure 12.6** top left) shows the highest magnitudes of streamflows of the four selected months, especially in the eastern side of the region, as a result of the summer rainfall regime. The July baseline map (**Figure 12.7** top left) shows low streamflow volumes in the tributaries, but greater flows in the mainstems of the larger river systems. The historical

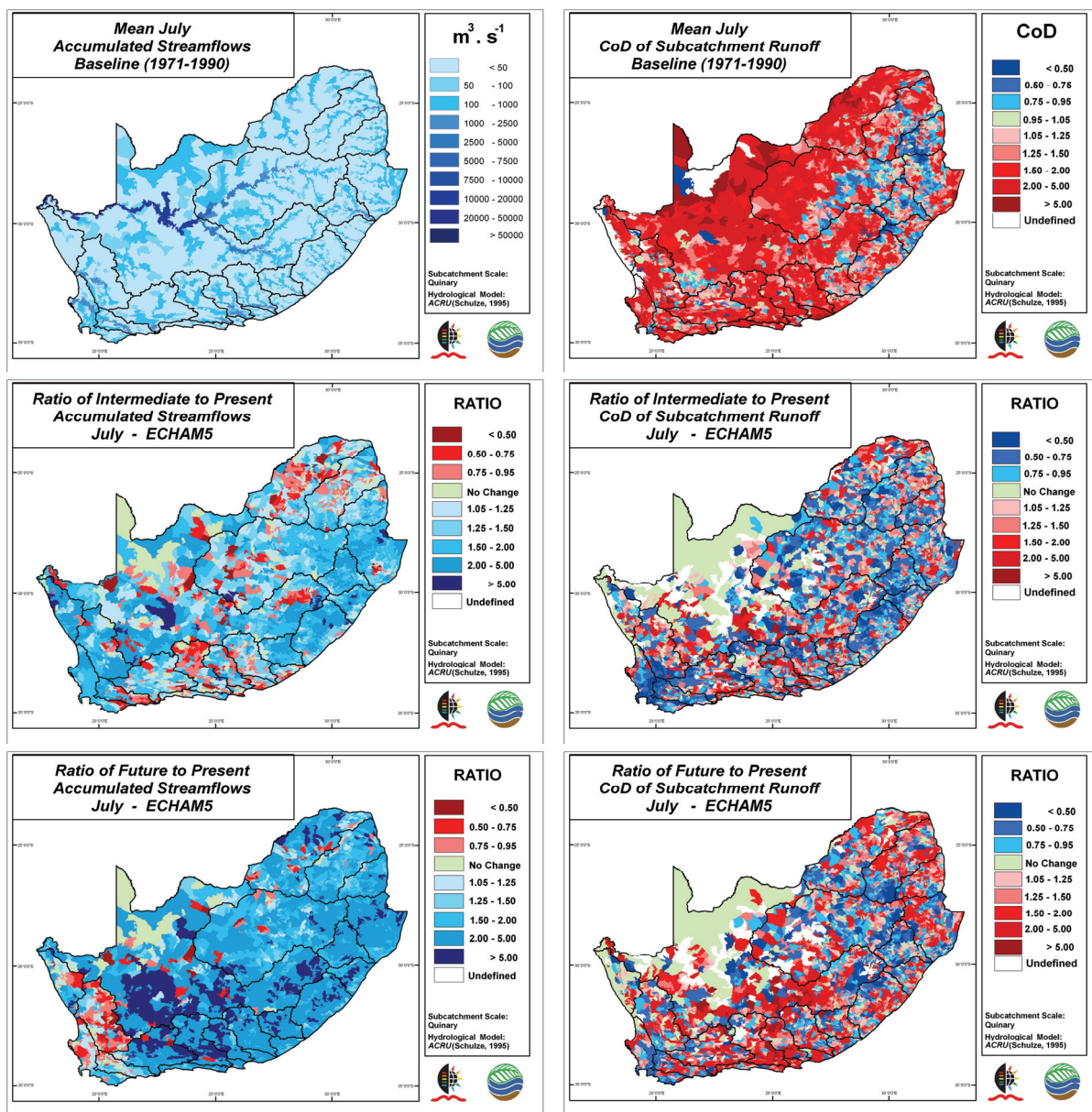


Figure 12.7 Mean July accumulated streamflows ($m^3 \cdot s^{-1}$) under baseline climatic conditions, as well as ratios of the intermediate future to present and more distant future to present accumulated streamflows derived with the ACRU model from ECHAM5 climate input (left hand maps), together with their respective Coefficients of Dispersion (right hand maps)

baseline climate maps for the months of April and October (**Figure 12.5** top left and right) display similar patterns of accumulated streamflows, but with one difference being that April indicates more streamflow to occur in the Northern Cape Province.

A ratio analysis of accumulated streamflows generated from the three ECHAM5 climate scenarios was performed for the four cardinal months and illustrates similar results to those found in the analysis of subcatchment runoff (cf. **Section 12.2.4**). The ratio analysis for January illustrates a distinct band of decreasing accumulated streamflows from the northeastern tip of South Africa to the Eastern Cape province in the intermediate future to present ratio analysis (**Figure 12.6** middle left),

with most Quinaries in this band experiencing a decrease in accumulated streamflows of between 5 and 50 %. This band is projected to shift westward to cover the southwestern parts of the Western Cape in the distant future to present scenario (**Figure 12.6** bottom left). The eastern seaboard of southern Africa is projected to experience an increase in accumulated flows in both the intermediate and more distant future climates projected by the ECHAM5 GCM. The ratio analysis for July indicates that most of the region can expect an increase in streamflows in the intermediate future (**Figure 12.7** middle left), with the band of decreasing streamflows becoming far less apparent. This wetting trend is projected to become stronger under the more distant future climate projected by the ECHAM5 GCM (**Figure 12.7** bottom left). April and October, the transitional months, show very similar results for both ratio analyses (**Figure 12.8** middle and bottom), with a decrease in streamflows projected for the Northern Cape and Eastern Cape provinces. Both months also project a decrease in runoff in the Western Cape in the more distant future, compared to the flows generated from the present climate from the ECHAM5 GCM. For the month of April projections indicate a general wetting on the east coast of southern Africa for both scenarios, but especially for the distant future to present analysis, where most Quinaries in this region are likely to experience an increase in streamflow by a factor of between 2 and 5 (**Figure 12.8** middle and bottom left). Compared to April, October indicates an even stronger wetting signal for both ratio analyses, except in the southwestern parts of the Western Cape.

A monthly analysis for the CoD of accumulated streamflows was performed for the months of January and July to determine whether any seasonal (intra-annual) differences or spatial patterns were evident at present and with future climate scenarios. Both January and July exhibit a high CoD for much of the region under present baseline climatic conditions (**Figures 12.6** and **12.7** top left), especially in the Northern Cape province, signifying that streamflow values between one year and the next are highly variable for these months. Similarly to the analysis for the CoD of monthly subcatchment runoff (**Section 12.2.4**), January shows lower CoD values of accumulated streamflows, of between 0.5 and 0.75, for the Western Cape in its non-rainy rainfall season, while July shows lower CoD for the eastern parts of southern Africa when they are in their dry season. The January ratio analysis of the CoD of accumulated streamflows does not reveal any clear regional trends, except that there seems to be an overall decrease in CoD, particularly for the distant future to present ratio analysis (**Figure 12.6** bottom right), over much of South Africa. July also does not exhibit any clear changes in inter-annual streamflows with climate change projected with the ECHAM5 GCM, except that the arid regions are projected to experience no change in accumulated streamflows under future climatic conditions owing to the general absence of streamflow in winter.

12.2.6 Ratios of baseflow to total subcatchment runoff (the Alt-BFI indicator)

The higher the ratio of a subcatchment's baseflow to the total subcatchment runoff (termed the "Alt-BFI" indicator of hydrological alteration), the more dependent the area is on groundwater contributing to sustaining streamflows. The baseline climate map of the Alt-BFI indicator shows important regional trends (**Figure 12.9** top left). The Western Cape province and western coastline, which have an average Alt-BFI of ~ 0.4-0.5, i.e. approximately 45%, display significantly higher values than the Alt-BFI values found in the remainder of the region under study. Both climate ratio maps of Alt-BFI project a similar magnitude of change for this indicator. The eastern half of the region is likely to experience a general increase Alt-BFI, while the western parts show that some Quinaries could experience a slight decrease in the ratio of baseflow to total subcatchment runoff. The Quinaries located in the Western Cape province and the western coastline, which showed high Alt-BFI values

for the present baseline climate, are projected not to experience any major changes in the intermediate and more distant future climates when runoff components are computed from the *ACRU* model using ECHAM5 climate input.

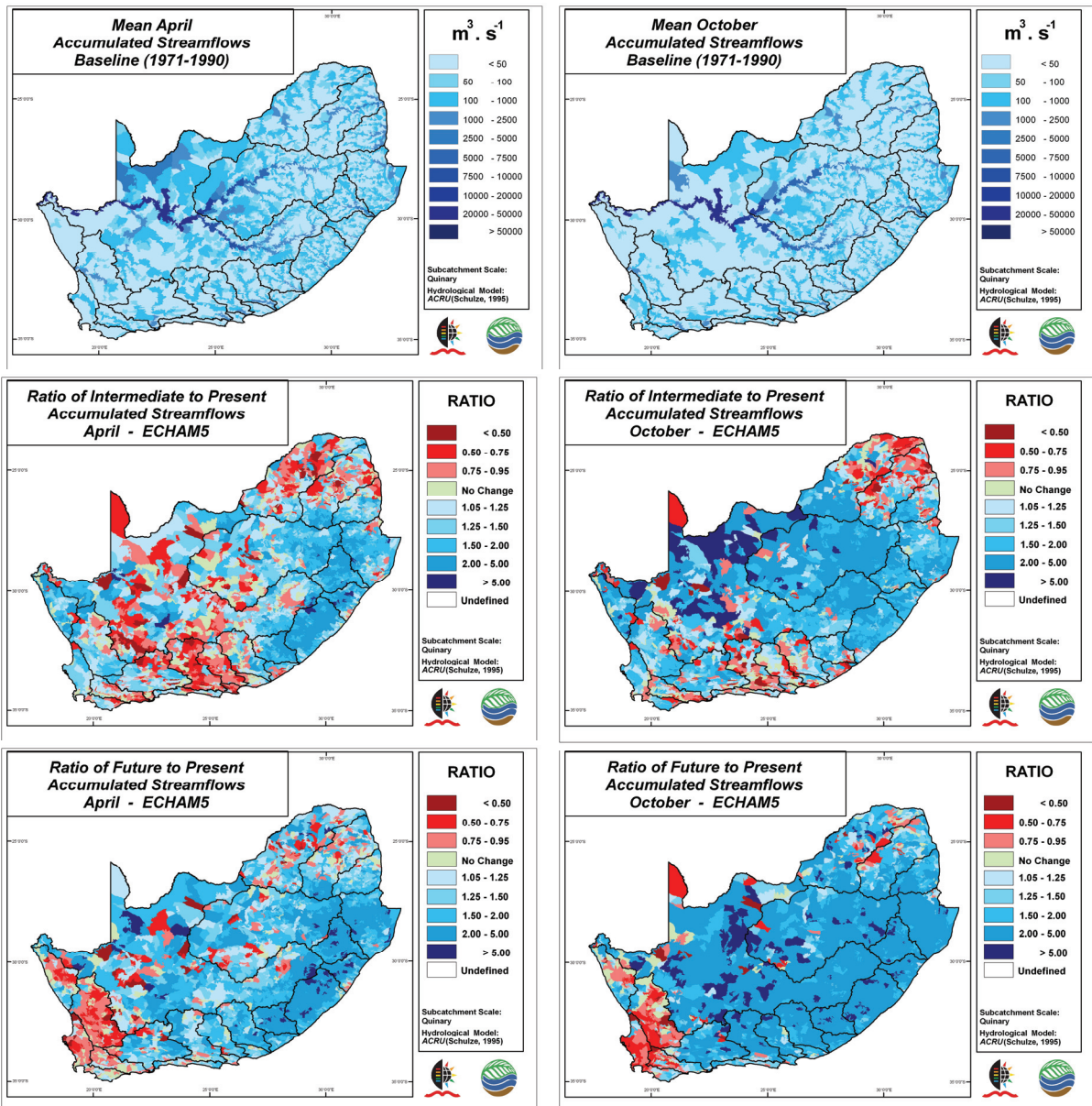


Figure 12.8 Mean April and October accumulated streamflows ($\text{m}^3.\text{s}^{-1}$) under baseline climatic conditions (top maps), as well as ratios of the intermediate future to present (middle row) and more distant future to present accumulated streamflows (bottom row) derived with the ACRU model from ECHAM5 climate input

12.3 High and Low Flows of Different Durations

12.3.1 Setting the scene

As in the previous section, the ACRU model (Schulze, 1995 and updates) was used to simulate means of annual high and low flows of different durations from the 5 838 Quinary Catchments which constitute the southern African study region, again using the climate scenarios summarised in **Section 12.1** and outlined in more detail in **Chapter 9**.

The duration of flow events is the period of time associated with a specific water condition in a stream (Richter *et al.*, 1996). The durations used in this research are based on the recommended durations

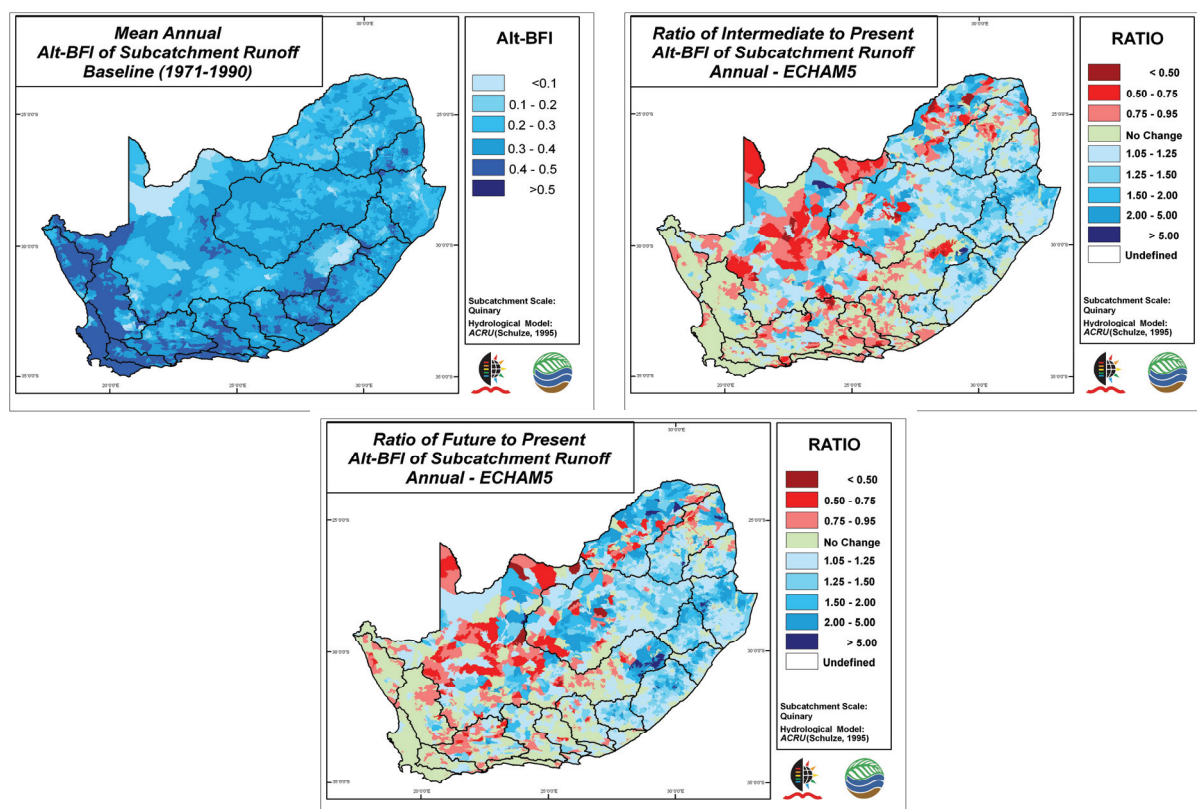


Figure 12.9 Ratios of mean annual subcatchment baseflow to total flow (Alt-BFI) under baseline climatic conditions (top left) and ratio changes of this relationship between intermediate future and present (top right) and more distant future and present climates, derived with the *ACRU* model from ECHAM5 climate input

from the developers of the IHA and attempt to represent natural cycles. They consist of the 1 day, 3 day, 7 day (weekly), 30 day (monthly) and 90 day (seasonal) extremes (The Nature Conservancy, 2005). The 1 day events are the maximum and minimum daily streamflow values that occur in any given year, while the multi-day events are the highest and lowest multi-day means of flows occurring in any given year (Taylor, 2006). The durations of flows are split into low and high flow conditions and both are analysed in this section. Both the means of the time series of annual minimum and maximum 1, 3, 7, 30 and 90 day average flows are mapped for southern Africa using the historical baseline climate data (1970-1990), as are the Coefficients of Dispersion (CoD) for these durations. In order to project likely changes over time in low and high flows for the selected durations under conditions of climate change, daily climate values from the ECHAM5 GCM's present, intermediate future and more distant future scenarios were input into the *ACRU* model and means of annual low and high flows for the respective durations were calculated using the accumulated streamflow output.

12.3.2 Means of annual low flows of different durations

Low flow conditions in South African rivers are a natural seasonal phenomenon, especially in areas with a distinct dry and wet season. Low flow conditions are an important component of a river's flow regime and can enable the recruitment of certain floodplain plants, as well as purging invasive (i.e. introduced) species from aquatic and riparian communities. Low flows can also concentrate prey into limited areas to benefit predators, as well as providing migration and spawning cues for fish (summarised from Taylor, 2006).

Figures 12.10-12.14 display the annual minimum 1, 3, 7, 30 and 90 day averages of accumulated low flows across southern Africa, the CoD of these flows, as well as the ratio comparisons from the three ECHAM5 climate scenarios for all the aforementioned durations of low flows. A comparison of each of the five durations of low flows reveals that they all exhibit similar overall trends. The historical baseline maps for the minimum 1, 3, 7, 30 and 90 day averages of accumulated streamflows (**Figures 12.10-12.14** top left) show that most tributaries located away from the mainstems of major river systems have low flows of less than $1 \text{ m}^3 \cdot \text{s}^{-1}$. The mainstems of the major river systems show the highest low flows, as would be expected for accumulated flows, especially in the Orange River Catchment. It should be noted that the magnitudes of the flow rates increase steadily as the duration increases (i.e. from the lowest for the 1 day to the higher values when low flows are averaged over a 90 day period), which again is to be expected.

The ratio maps of intermediate future to present ECHAM5 climates for the minimum 1, 3, 7, 30 and 90 day averages of accumulated streamflows (**Figures 12.10-12.14** middle left) indicate that there could be an overall increase in minimum flows for all flow durations, especially on the eastern side of South Africa. However, the Eastern Cape and Northern Cape provinces do contain pockets of Quinaries indicating a projected decrease in flow in the intermediate future.

The ratio maps of distant future to present ECHAM5 climates (**Figures 12.10-12.14** bottom left) show that virtually all Quinary Catchments are projected to experience an increase in minimum accumulated streamflows for all flow durations. The Western Cape is the major exception and this ratio analysis indicates a distinct projected decrease in flows with the ECHAM5 GCM of between 5 and 25% for all flow durations for this region. KwaZulu-Natal and the Eastern Cape show a strong wetting signal with flows derived from ECHAM5, with the annual minima of accumulated streamflows projected to increase by a factor of between 2 and 5 for all flow durations.

The CoDs for the annual minima of 1, 3, 7, 30 and 90 day accumulated streamflows using the historical baseline climate scenario (**Figures 12.10-12.14** top right) depicts the eastern and the coastal regions of southern Africa to experience less inter-annual variability in minimum accumulated streamflows compared to those of the Northern Cape. The Northern Cape experiences erratic rainfalls from one year to the next and this translates into the high CoD for all minimum flow durations there. The ECHAM5 ratio maps for the minimum 1, 3, 7, 30 and 90 day averages of annual accumulated streamflows (**Figures 12.10-12.14** middle and bottom right) do not display clear overall trends or spatial patterns.

12.3.3 Means of annual high flows of different durations

As in the case of low flows, high flows and high flow pulses are a critical component of the natural flow regimes of South African rivers. High flows are a major determining factor in the physical characteristics of the river channels and pools, as well as the size and combination of streambed substrates such as sand, gravel and cobble. High flows are also required to restore water quality to more normal conditions after prolonged low flows by flushing out waste products and pollutants. This flushing can also transport food and habitat structure into the channel, as well as preventing riparian vegetation from encroaching into the channel. High flows are also very important for organisms which inhabit lotic systems as they can provide migration and spawning cues and trigger a new phase in a species life cycle (summarised from Taylor, 2006).

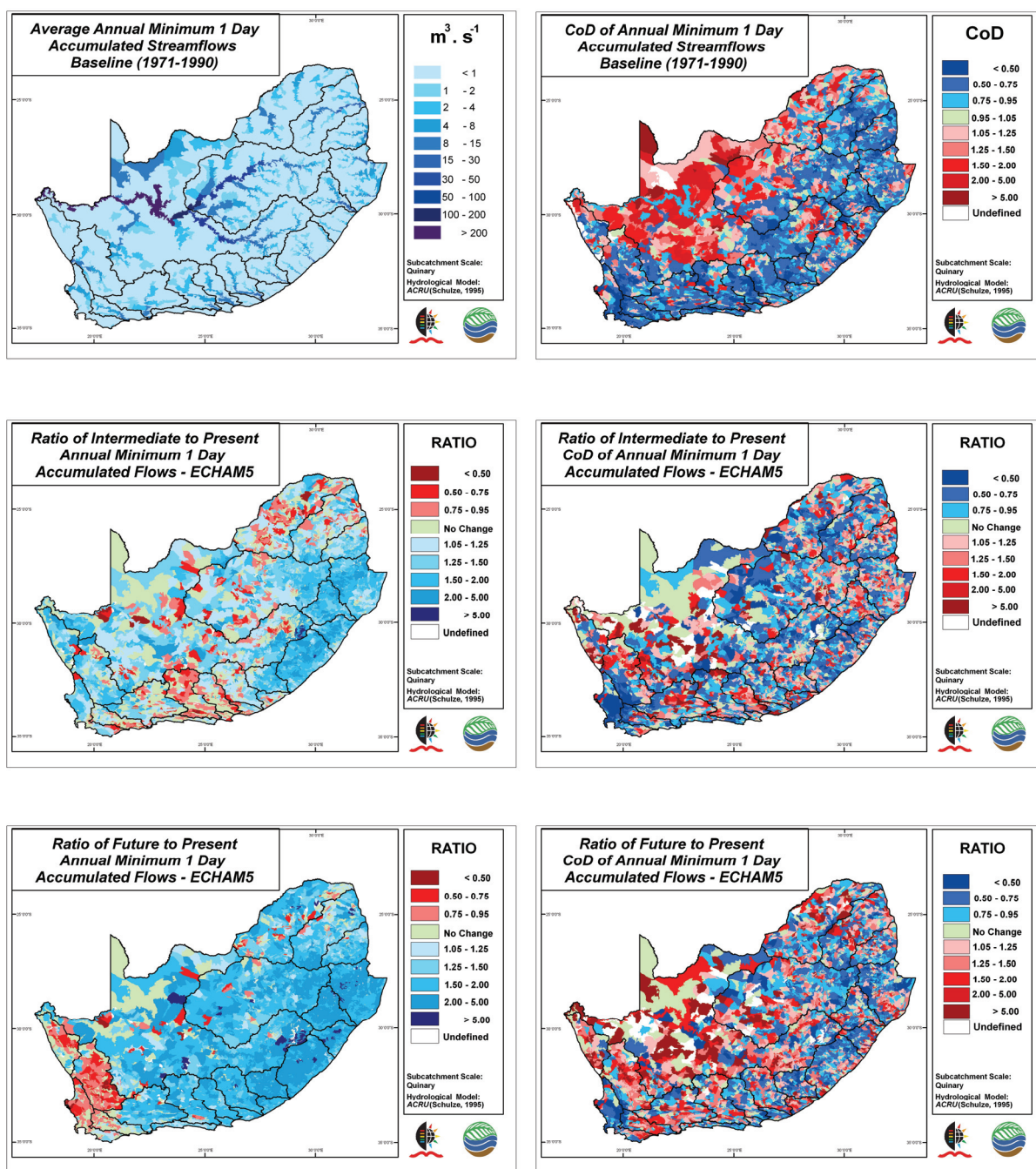


Figure 12.10 Average annual minimum 1 day accumulated streamflows ($\text{m}^3 \cdot \text{s}^{-1}$) under baseline climatic conditions (top left), as well as ratios of the intermediate future to present and more distant future to present of this indicator, derived with the *ACRU* model from ECHAM5 climate input (middle and bottom left), together with their respective Coefficients of Dispersion (right hand maps)

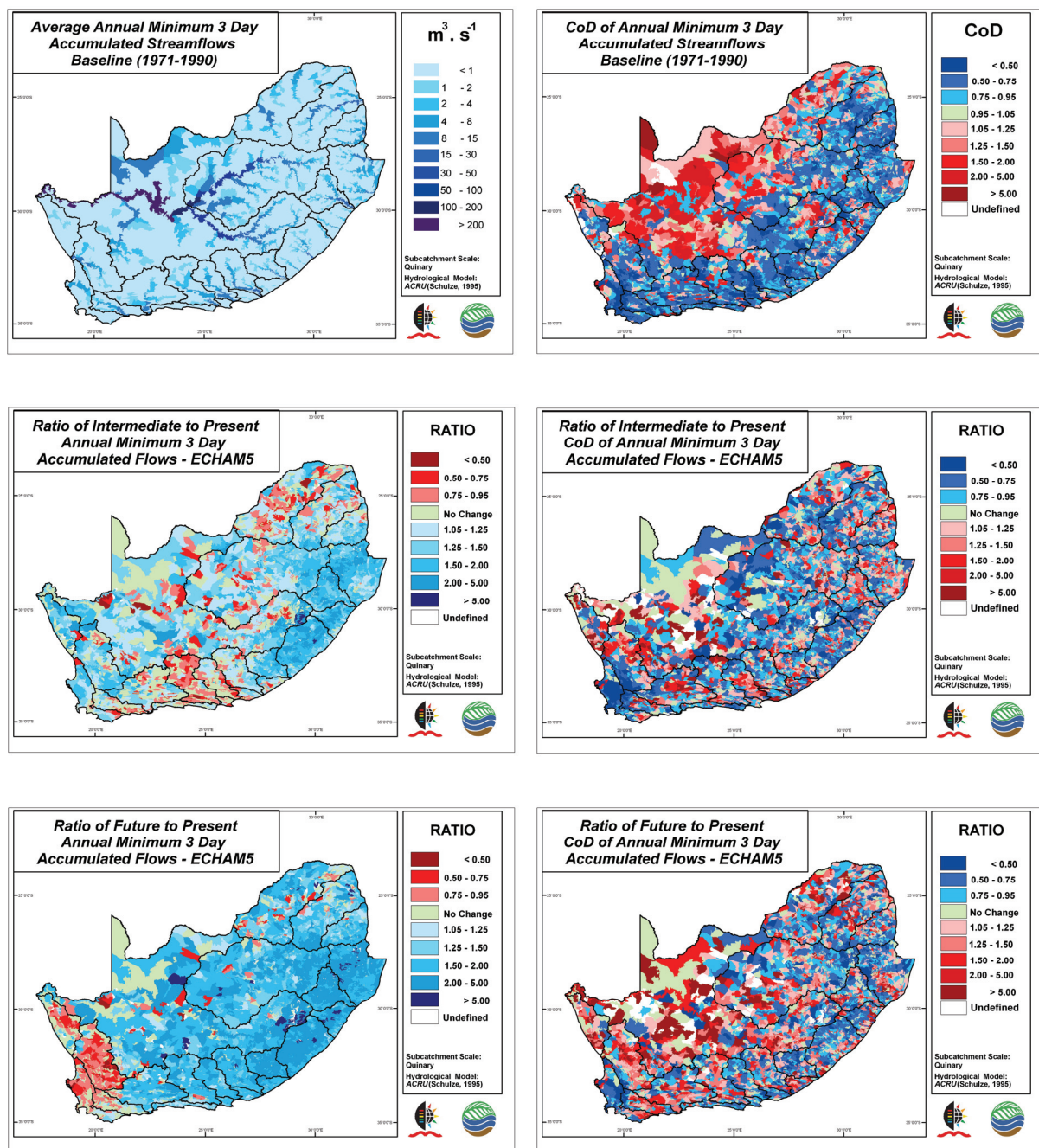


Figure 12.11 Average annual minimum 3 day accumulated streamflows ($\text{m}^3 \cdot \text{s}^{-1}$) under baseline climatic conditions (top left), as well as ratios of the intermediate future to present and more distant future to present of this indicator, derived with the *ACRU* model from ECHAM5 climate input (middle and bottom left), together with their respective Coefficients of Dispersion (right hand maps)

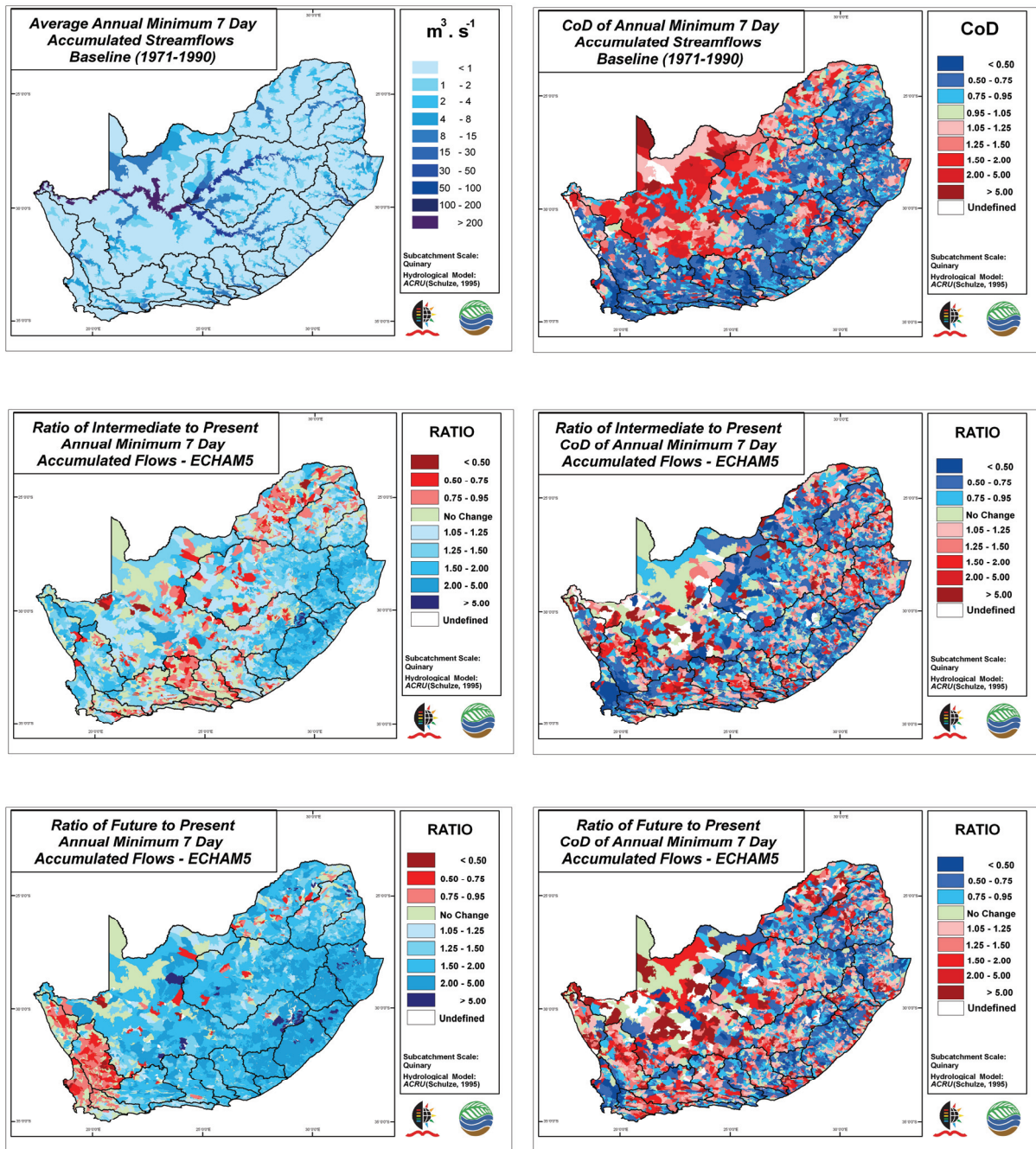


Figure 12.12 Average annual minimum 7 day accumulated streamflows ($\text{m}^3 \cdot \text{s}^{-1}$) under baseline climatic conditions (top left), as well as ratios of the intermediate future to present and more distant future to present of this indicator, derived with the ACRU model from ECHAM5 climate input (middle and bottom left), together with their respective Coefficients of Dispersion (right hand maps)

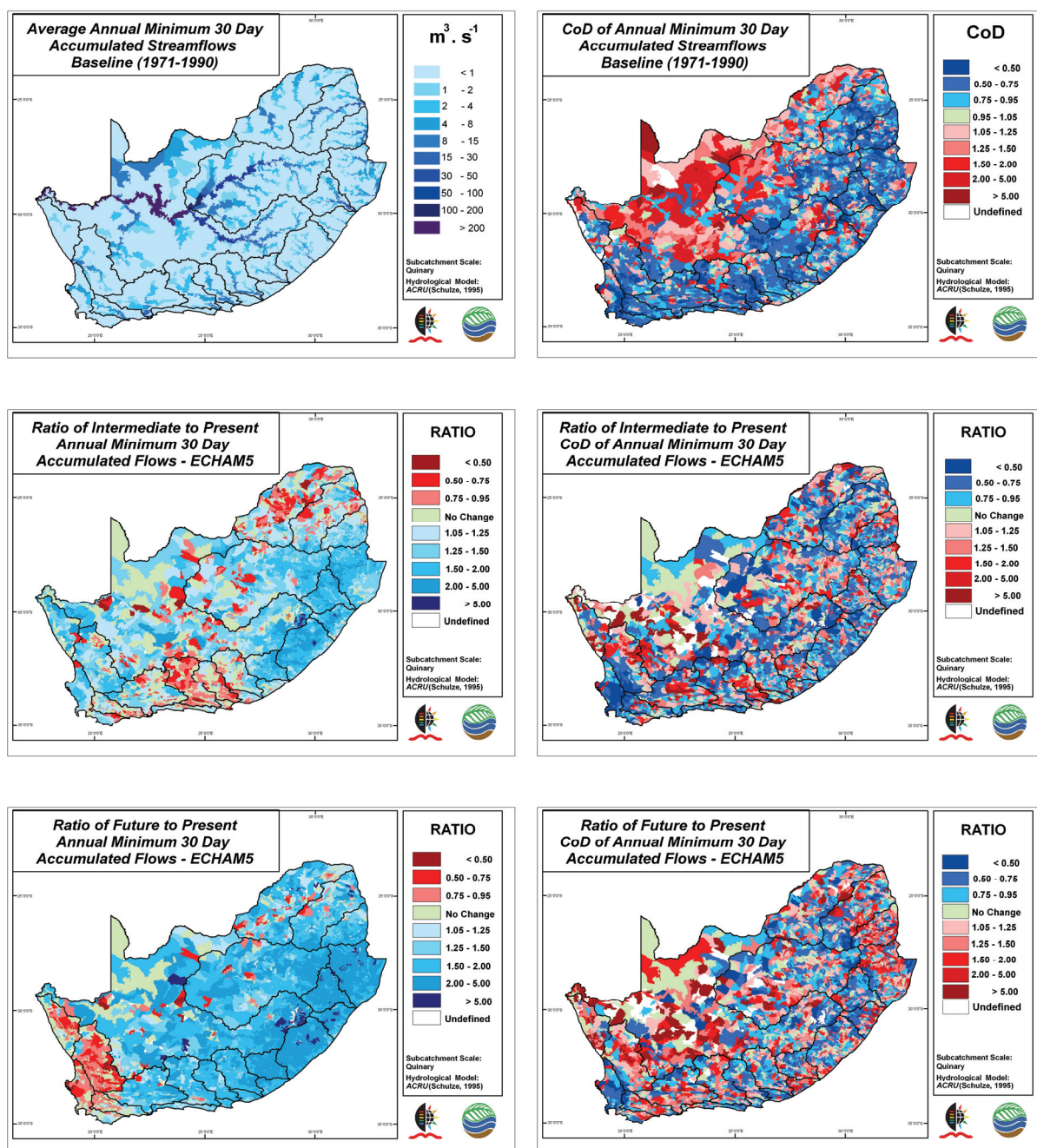


Figure 12.13 Average annual minimum 30 day accumulated streamflows ($\text{m}^3 \cdot \text{s}^{-1}$) under baseline climatic conditions (top left), as well as ratios of the intermediate future to present and more distant future to present of this indicator, derived with the ACRU model from ECHAM5 climate input (middle and bottom left), together with their respective Coefficients of Dispersion (right hand maps)

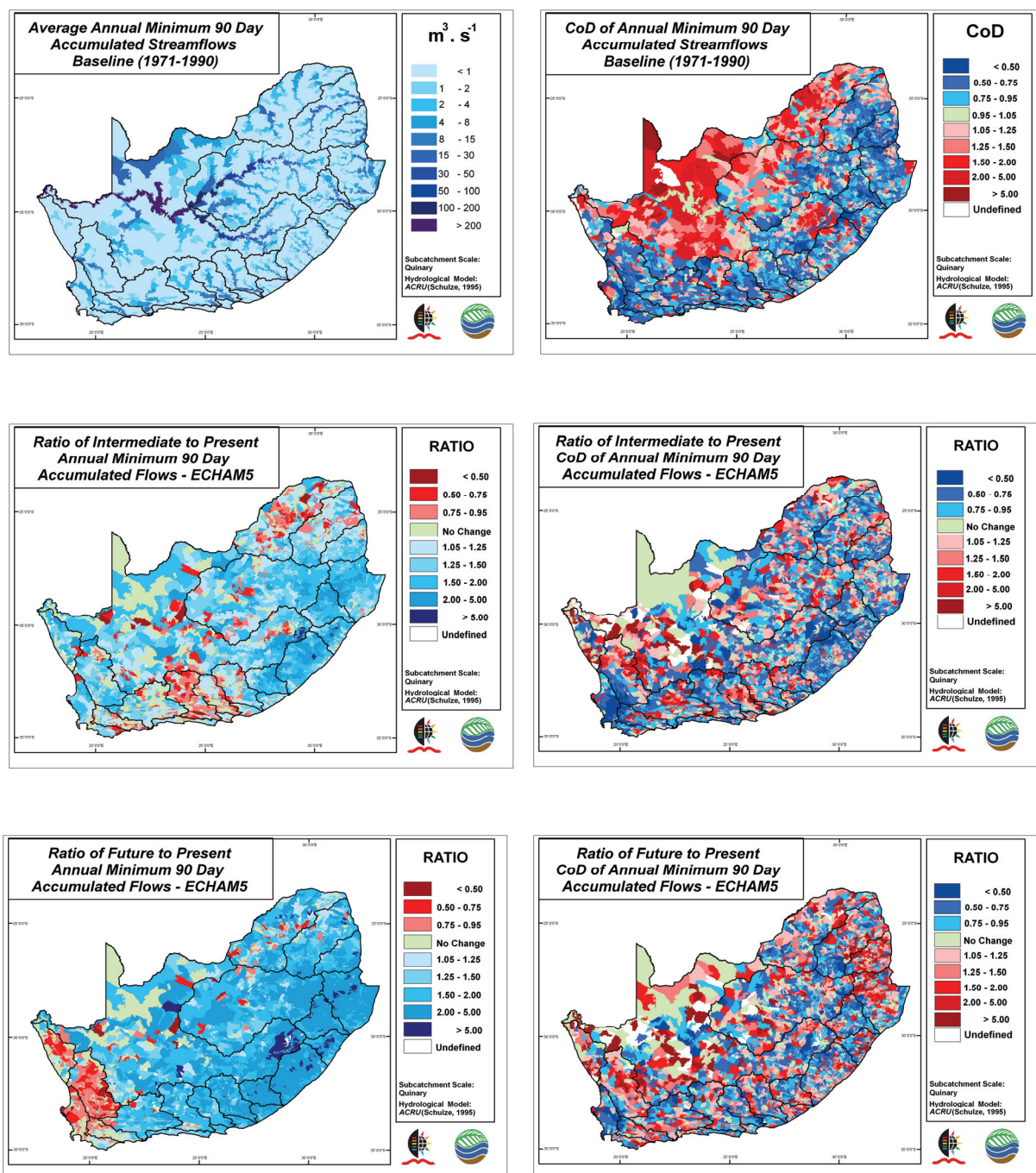


Figure 12.14 Average annual minimum 90 day accumulated streamflows ($\text{m}^3 \cdot \text{s}^{-1}$) under baseline climatic conditions (top left), as well as ratios of the intermediate future to present and more distant future to present of this indicator, derived with the *ACRU* model from ECHAM5 climate input (middle and bottom left), together with their respective Coefficients of Dispersion (right hand maps)

Figures 12.15-12.19 display the averages of annual maximum 1, 3, 7, 30 and 90 day annual accumulated streamflows for southern Africa, the CoDs of these flows as well as the ratio comparisons for the three ECHAM5 climate scenarios for all the aforementioned flow durations. A comparison of each of the five maximum flow durations and the ratio maps reveals that all flow durations exhibit similar trends.

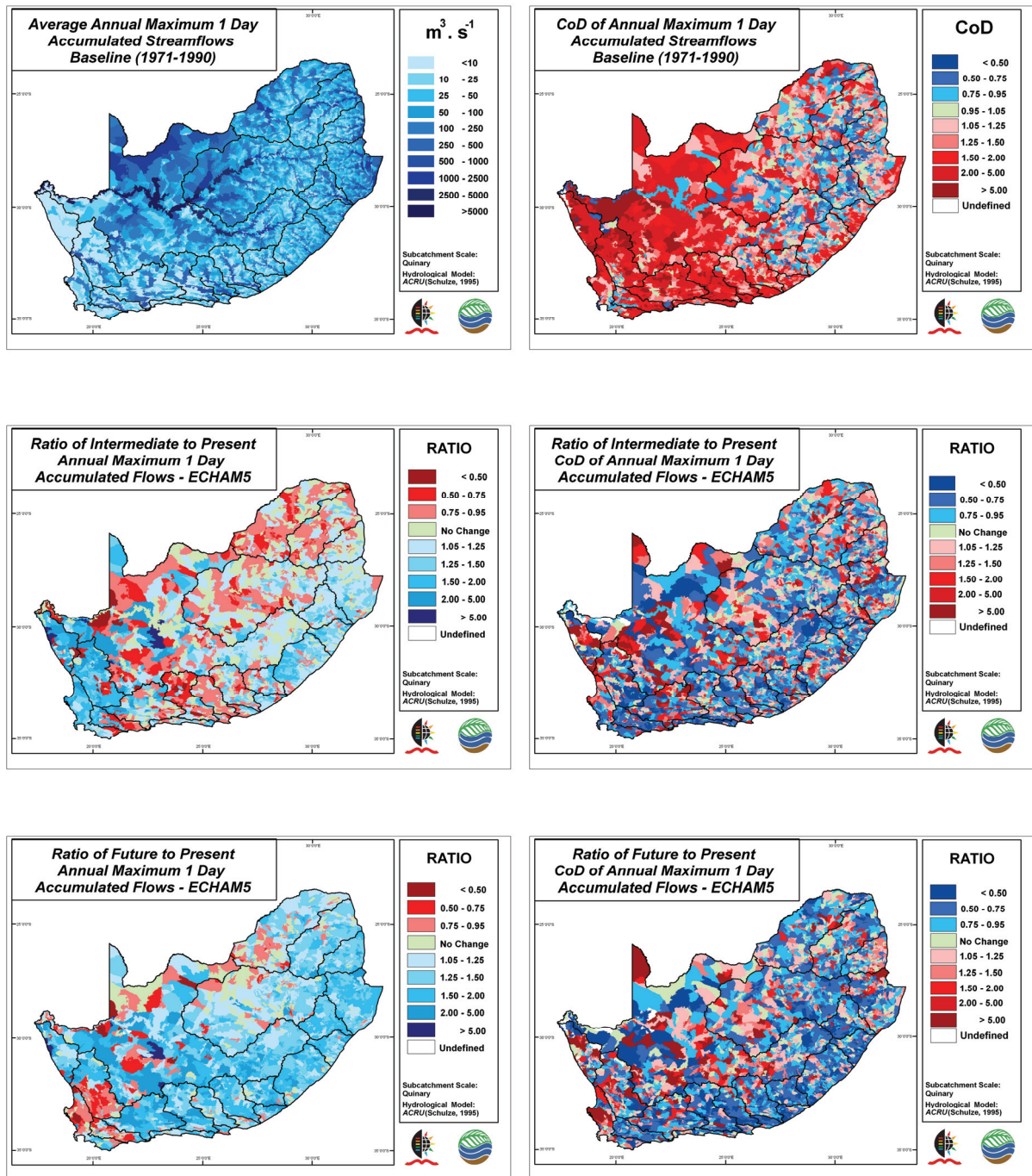


Figure 12.15 Average annual maximum 1 day accumulated streamflows ($\text{m}^3\cdot\text{s}^{-1}$) under baseline climatic conditions (top left), as well as ratios of the intermediate future to present and more distant future to present of this indicator, derived with the *ACRU* model from ECHAM5 climate input (middle and bottom left), together with their respective Coefficients of Dispersion (right hand maps)

The historical baseline maps for the maximum 1, 3, 7, 30 and 90 day averages of annual accumulated streamflows (**Figures 12.15-12.19** top left) display distinctly wetter patterns than the low flow duration maps presented in **Section 12.3.2**. The mainstems of the primary river systems show the greatest magnitudes of flow, but some streamflow accumulation is also discernible in smaller tributaries, especially for the 1 and 3 day duration maps (**Figures 12.15** and **12.16**). A comparison of

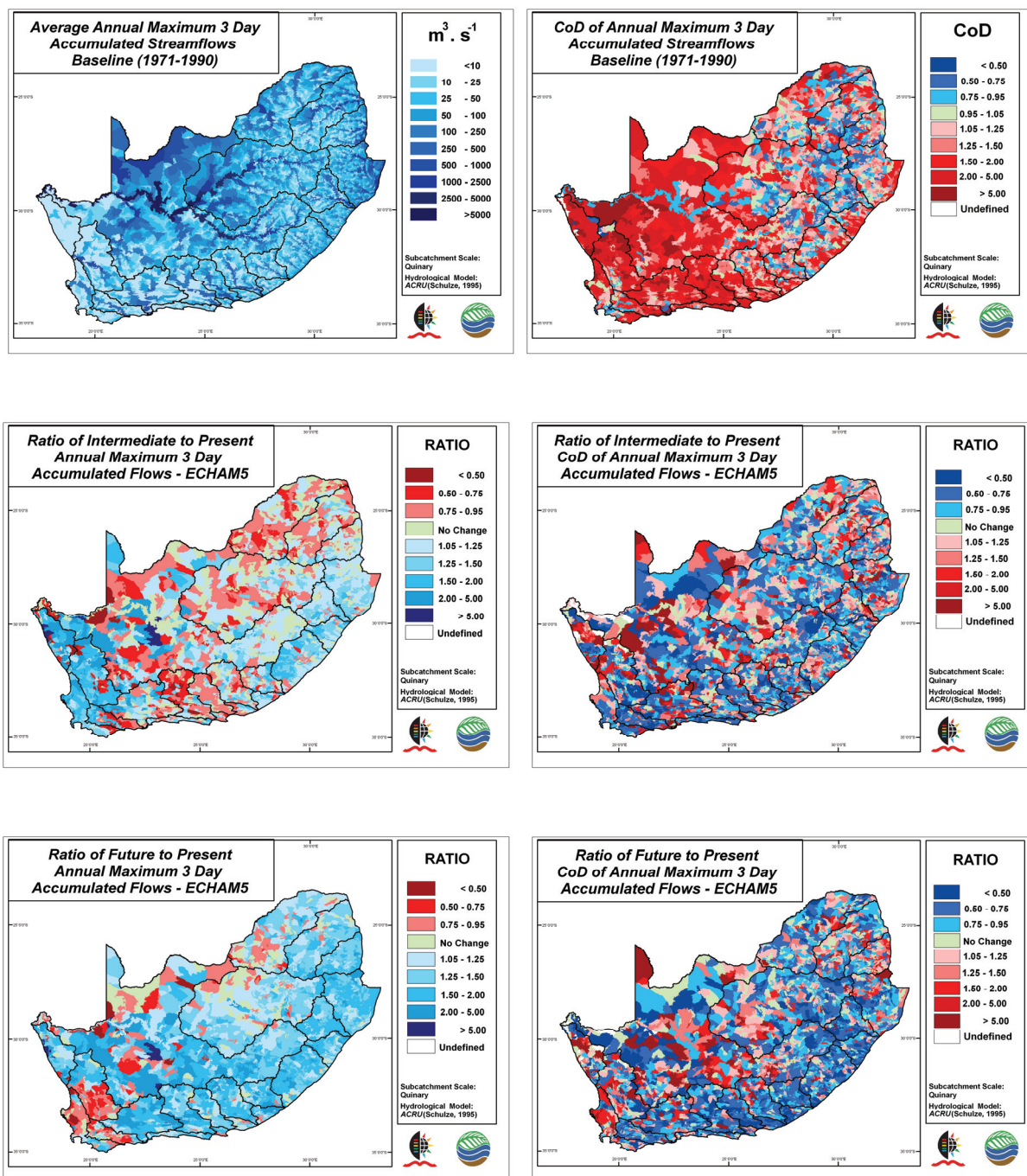


Figure 12.16 Average annual maximum 3 day accumulated streamflows ($m^3 \cdot s^{-1}$) under baseline climatic conditions (top left), as well as ratios of the intermediate future to present and more distant future to present of this indicator, derived with the *ACRU* model from ECHAM5 climate input (middle and bottom left), together with their respective Coefficients of Dispersion (right hand maps)

the baseline maps of maximum flows shows that the averaged magnitudes of flow rates decreases steadily as the duration of maximum flows increases from the 1 day to the 90 day period, which is to be expected.

The ratio maps generated from intermediate future to present ECHAM5 climates for maximum 1, 3, 7, 30 and 90 day annually averaged accumulated streamflows (**Figures 12.15-12.19** middle left)

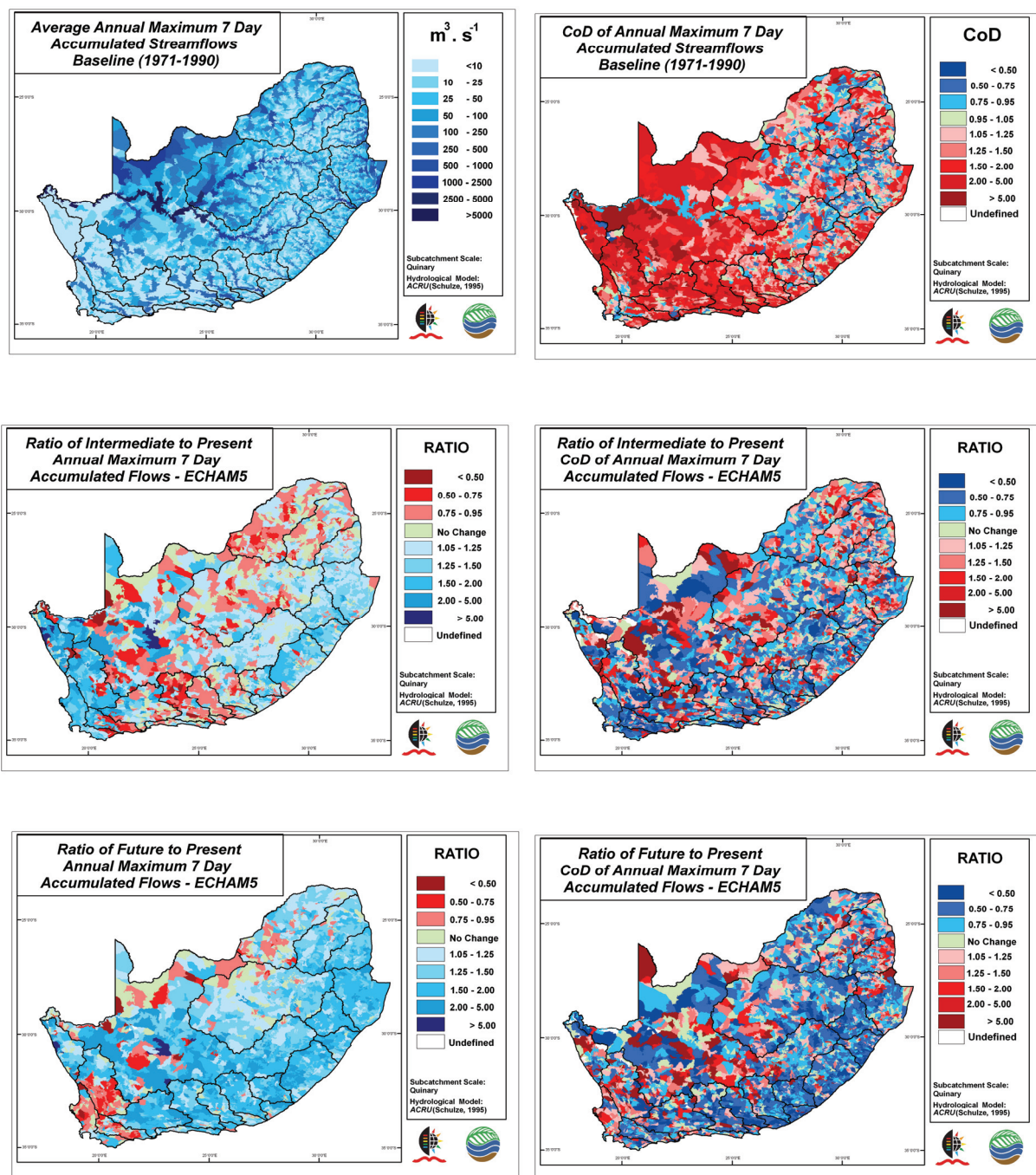


Figure 12.17 Average annual maximum 7 day accumulated streamflows ($\text{m}^3 \cdot \text{s}^{-1}$) under baseline climatic conditions (top left), as well as ratios of the intermediate future to present and more distant future to present of this indicator, derived with the ACRU model from ECHAM5 climate input (middle and bottom left), together with their respective Coefficients of Dispersion (right hand maps)

indicate there could be an increase in maximum flows in KwaZulu-Natal and along the west coast of South Africa for all durations. These ratio maps also indicate a band of Quinaries, stretching from the northeastern tip of South Africa through to the Eastern Cape for which a decrease in maximum flows for all durations is projected from ECHAM5. This band of Quinaries is more apparent and contiguous for the shorter durations of 1 and 3 days.

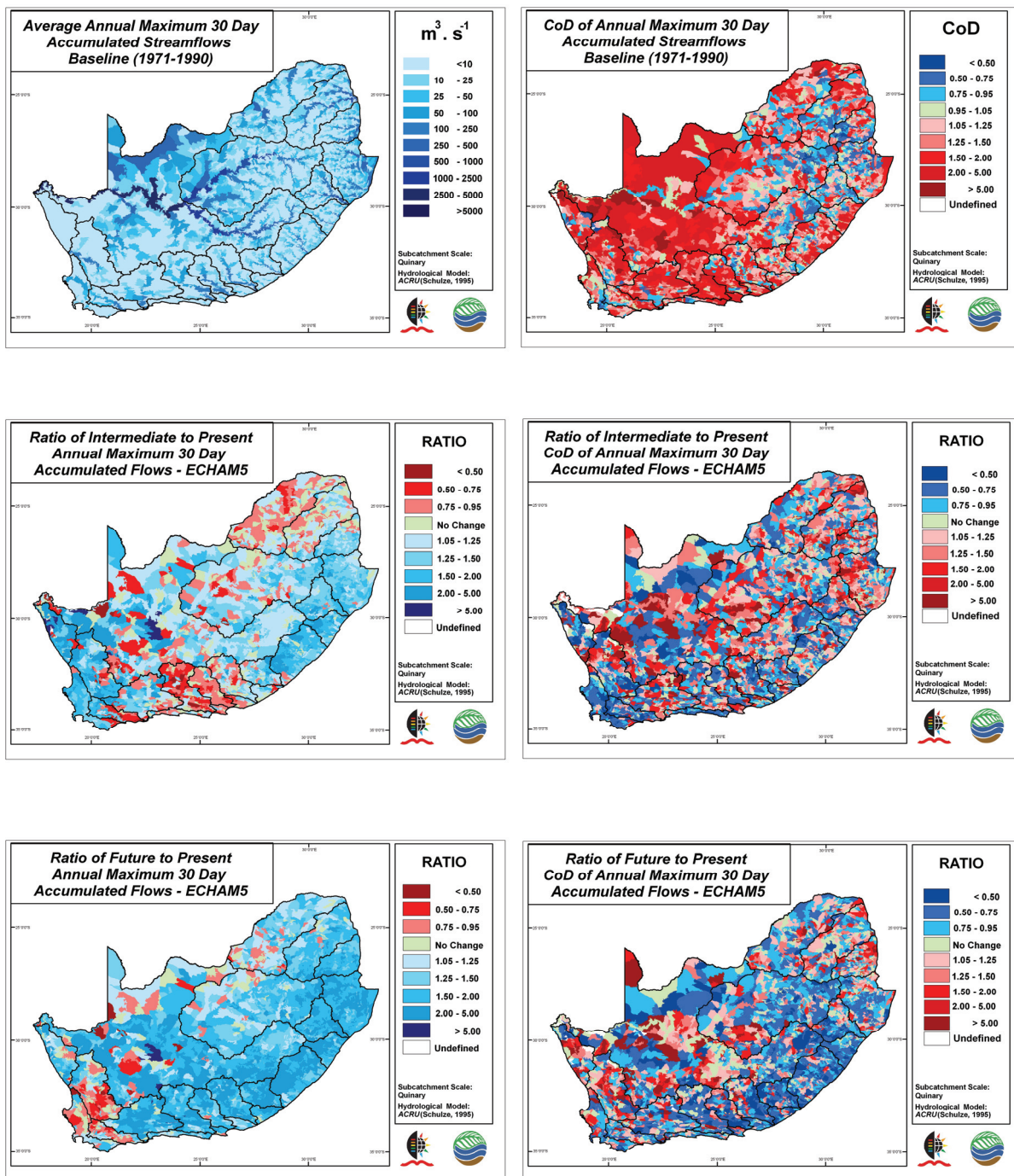


Figure 12.18 Average annual maximum 30 day accumulated streamflows ($\text{m}^3 \cdot \text{s}^{-1}$) under baseline climatic conditions (top left), as well as ratios of the intermediate future to present and more distant future to present of this indicator, derived with the *ACRU* model from ECHAM5 climate input (middle and bottom left), together with their respective Coefficients of Dispersion (right hand maps)

The ratio maps from the distant future to present ECHAM5 climates (**Figures 12.15-12.19** bottom left) show that virtually all Quinary Catchments are projected to experience an increase in their maximum annual accumulated streamflows for all flow durations. The Western Cape is again the major exception and, as in the case of the minimum flow ratio analysis, displays a distinct decrease in maximum averaged annual flows of between 5 and 25% for all flow durations. Across the remainder

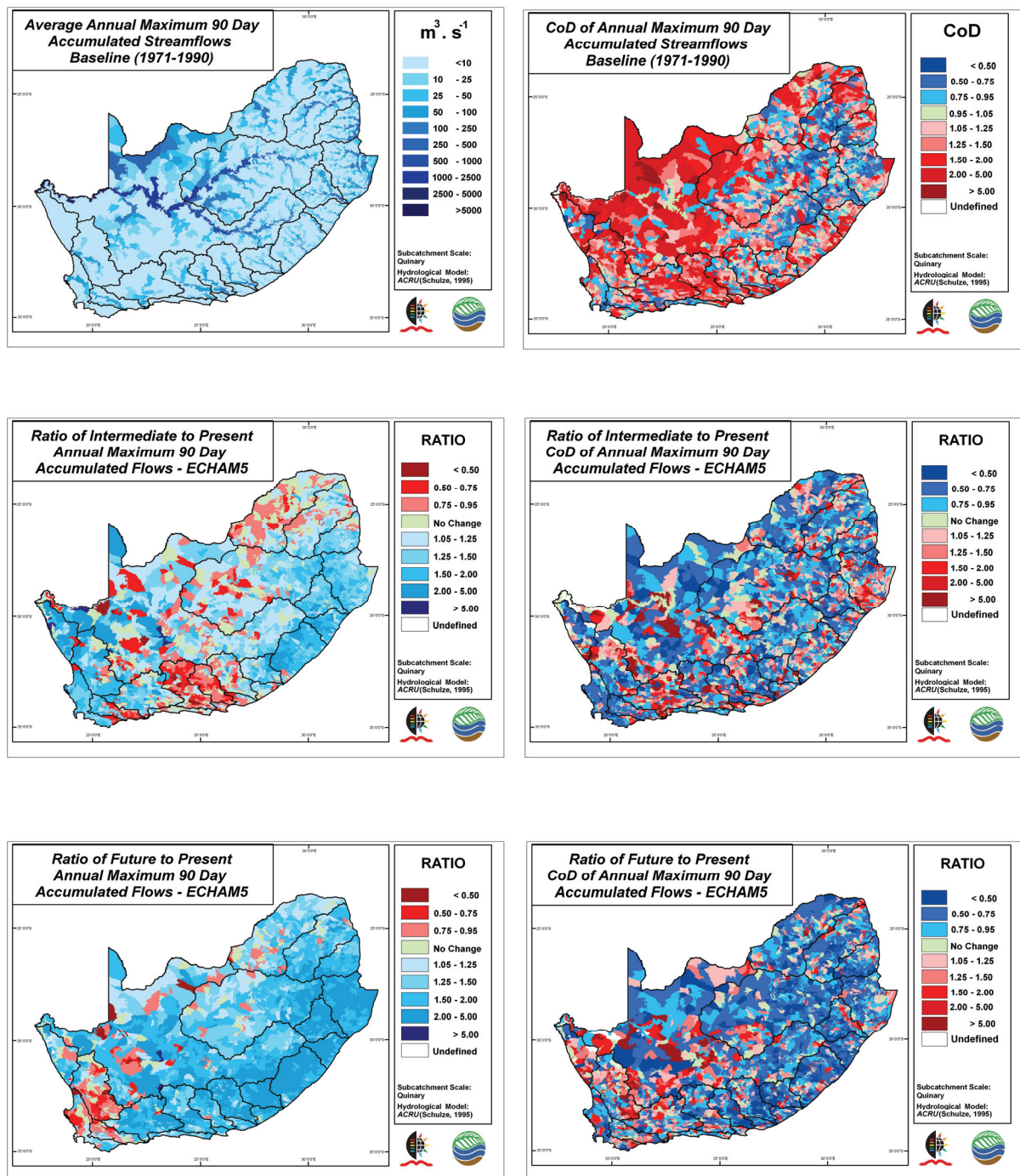


Figure 12.19 Average annual maximum 90 day accumulated streamflows ($\text{m}^3 \cdot \text{s}^{-1}$) under baseline climatic conditions (top left), as well as ratios of the intermediate future to present and more distant future to present of this indicator, derived with the *ACRU* model from ECHAM5 climate input (middle and bottom left), together with their respective Coefficients of Dispersion (right hand maps)

of the study area a wetting signal is indicated, with maximum accumulated streamflows expected to increase by a factor of between 1.05 and 2.

The CoDs for the maximum annual 1, 3, 7, 30 and 90 day accumulated streamflows using the historical baseline climate scenario (**Figures 12.15-12.19** top right) indicates the eastern side southern Africa to experience lower inter-annual variability of the maximum accumulated streamflows

compared to the western half of the region. The western half shows a high CoD of between 2 and 5 for all maximum flows with durations from 1 to 90 days. This large CoD implies that high flows for the various durations for this region are highly variable from year to year and this makes it difficult to manage river systems in this area. The ratio maps derived from intermediate future to present

ECHAM5 climates for the CoD for the maximum annual 1, 3, 7, 30 and 90 day accumulated streamflows (**Figures 12.10-12.19** middle right) do not show definite spatial patterns. However, the CoD ratio maps of distant future to present ECHAM5 climates (**Figures 12.10-12.19** bottom right) suggest a decrease in the CoD for most Quinaries, particularly along the eastern coastline.

In this chapter the potential impacts of climate change on the magnitudes and durations of flow were assessed using the baseline climate conditions and the ECHAM5 climate scenarios. This spatial assessment was performed for the 5 838 hydrologically interlinked and cascading Quinary Catchments which constitute the southern Africa study region. **Section 12.2** focussed on the magnitudes of flow events and was performed for both individual catchment runoff and accumulated streamflows. **Section 12.3** investigated the durations of flow events using accumulated streamflows for the 1, 3, 7, 30 and 90 day flow durations for both low and high flows.

The main findings of this chapter are summarised in **Table 12.1**.

Chapter 13, which follows, is the third results chapter and assesses the potential impacts of climate change on water temperature related indicators in the Thukela Catchment, again using the climate scenarios derived from the ECHAM5 GCM.

12.4 References

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Table 12.1 Summary of results for the ecological flow indicators

Ecological Flow Indicator		Intermediate: Present	Future: Present
Magnitude of Flow Events	Annual Subcatchment Runoff	Moderate increase projected in the eastern half of southern Africa. Moderate decrease projected for a band of Quinaries running from Limpopo to the Eastern Cape.	A significant increase by a factor of between 2 and 5 is projected throughout southern Africa, but excluding the Western Cape, which could experience a decrease by 25-50%.
	Annual Accumulated Streamflows	Moderate increase projected in the eastern half of southern Africa. Moderate decrease projected for a band of Quinaries running from Limpopo to the Eastern Cape.	A significant increase by a factor of between 2 and 5 is projected throughout southern Africa, but excluding the Western Cape, which could experience a decrease by 25-50%.
	CoD of Annual Subcatchment Runoff	Results do not display clear overall trends, but most Quinaries throughout southern Africa could experience a decrease in CoD.	Results do not display clear overall trends, but most Quinaries throughout southern Africa could experience a decrease in CoD.
	CoD of Annual Accumulated Streamflows	Results do not display clear overall trends, but most Quinaries throughout southern Africa could experience a decrease in CoD.	Results indicate most Quinaries throughout southern Africa could experience a decrease in CoD.
	Annual Alt-BFI	Eastern half of the country could experience an increase, while no significant change is projected for the Western and Eastern Cape.	Eastern half of the country could experience an increase, while the no significant change is projected for the Western and Eastern Cape.
Duration of Flow Events	Annual Low Flow Conditions	Moderate increase projected in the eastern half of southern Africa by approximately 50% for all flow durations. Moderate decrease projected for a large band of Quinaries running from Limpopo to the Eastern Cape for all flow durations.	A significant increase by a factor of between 2 and 5 is projected throughout southern Africa, but excluding the Western Cape, which could experience a decrease in flows by 25-50% for all flow durations.
	Annual High Flow Conditions	Moderate increase projected in the eastern half of southern Africa by approximately 50% for all flow durations. Moderate decrease projected for a large band of Quinaries running from Limpopo to the Eastern Cape for all flow durations.	A significant increase by a factor of between 2 and 5 is projected throughout southern Africa, but excluding the Western Cape, which could experience a decrease in flows by 25-50% for all flow durations.
	CoD of Annual Low Flow Conditions	Results do not display clear overall trends, but most Quinaries throughout southern Africa could experience a decrease in CoD for all flow durations.	Results indicate most Quinaries throughout southern Africa could experience a decrease in CoD for all flow durations.
	CoD of Annual High Flow Conditions	Results do not display clear overall trends, but most Quinaries throughout southern Africa could experience a decrease in CoD for all flow durations.	Results indicate most Quinaries throughout southern Africa could experience a decrease in CoD for all flow durations.

CHAPTER 13 RESULTS 3: SPATIAL CHANGES IN WATER TEMPERATURE INDICATORS WITH CLIMATE CHANGE IN THE THUKELA CATCHMENT USING OUTPUT FROM THE ECHAM5/MPI-OM GENERAL CIRCULATION MODEL

K.R. Barichievy, R.E. Schulze and R.P. Kunz

13.1 Introduction to Spatial Analyses of Water Temperature Related Indicators

This Chapter is devoted to results from the water temperature related indicators. Because simulations on water temperature are computationally highly intensive, the spatial analysis has been confined to a single Water Management Area in South Africa, viz. the Thukela Catchment, the choice and characteristics of which were detailed in **Chapter 5**. Spatial analyses were performed on the following indicators:

- Mean air temperature,
- Individual subcatchment runoff,
- Accumulated streamflows,
- Individual subcatchment runoff water temperature, a
- Water Temperature Index for individual subcatchment runoff, a
- Water Temperature Index for accumulated streamflows, and
- Mixed water temperature.

Each indicator was analysed separately, with a brief description of the indicator being provided at the beginning of each sub-section. The spatial analysis was performed for the following scenarios (cf. **Chapter 9** for full description):

- Baseline (i.e. historical observed) Climate (1971-1990),
- Present Climate (1971-1990) from the ECHAM5/MPI-OM GCM, hereafter referred to as ECHAM5, an
- Intermediate Future Climate (2046-2065), and a more
- Distant Future Climate (2081-2100).

Each analysis was performed for mean annual responses and for those of four selected cardinal months, with January representing mid-summer conditions, April considered typical of autumn, July of mid-winter and October of spring. The annual results show overall trends for each scenario while the monthly time scale focuses on intra-annual differences. A comparison between the baseline historical scenario and the present climate generated by the GCM illustrates how well ECHAM5 is simulating the historically observed climate.

The spatial analysis for all water temperature related indicators comprises a ratio comparison, at mean annual level, between the three ECHAM5 climate scenarios, more specifically the ratios of intermediate future to present, more distant future to present and distant to Intermediate future climates, in order to determine how a particular indicator is projected to be changing from one scenario to the next. The monthly analysis similarly consists of comparisons between the baseline and present GCM scenarios for purposes of validation, as well as ratio comparisons between the Intermediate to Present and the Future to Present climate scenarios to assess spatial trends and projected rates of changes of the water temperature related indicators.

On the selection of the ECHAM5 GCM the following should be noted and is repeated from **Chapter 12**: Of the downscaled daily output from five GCMs received for this project from the Climate Systems Analysis Group at the University of Cape Town (cf. **Chapter 9**), only the output from the ECHAM5/MPI-OM GCM had gone through all the computationally exacting and highly time consuming configuration procedures needed for hydrological climate change applications with the ACRU model towards the end of 2008 when the water temperature analyses were performed. ECHAM5 was thus the only GCM the required output of which was available for this research. ECHAM5 was selected because of the five GCMs received it represents relatively “middle of the road” future rainfall scenarios for southern Africa, with some of the other GCMs projecting drier and others wetter future rainfall conditions.

The limitations of using output from a single GCM for impact studies are well documented (e.g. Hewitson *et al.*, 2005; Schulze *et al.*, 2007; IPCC, 2007) and are well appreciated by the project team. However, this report has its focus on development of techniques rather than on the certainty or uncertainty of results.

Note that on all maps which follow the term “Intermediate” refers to the intermediate future climate scenario while “Future” refers to the more distant future climate scenario.

13.2 Mean Air Temperature

Mean daily air temperature (°C) is calculated by averaging the daily maximum and minimum air temperatures. Mean air temperature is an important factor for a number of hydrological and ecological processes such as evaporation and growth rates (cf. Schulze, 2007).

13.2.1 Mean annual air temperature

Figure 13.1 displays the mean annual air temperature (MAT) for the 258 Quinary Catchments making up the Thukela, for the four scenarios described in **Chapter 9**. When comparing MAT from present baseline climate (**Figure 13.1** top left) with that from the present ECHAM5 climate (**Figure 13.1** top right), the results indicate that the ECHAM5 GCM is performing well, with a slight under-simulation of MAT in the west of the catchment.

Overall, however, there is a close correlation between the MAT from historical air temperature data and that simulated from the GCM. Both the historical baseline and ECHAM5 present scenarios indicate that the high altitude Drakensberg areas in the west experience the lowest MATs (+/- 11°C) and that air temperatures increase towards the coast (+/- 21°C), which is expected. A comparison between the ECHAM5 scenarios indicates a strong warming trend over time, particularly in the central parts of the Thukela Catchment, with the ECHAM5 distant future climate scenario showing the greatest deviation from that of the present climate.

13.2.2 Projected changes in mean annual air temperatures in future

Figure 13.2 displays differences in MATs between the three ECHAM5 climate scenarios for the Thukela Catchment. All three maps indicate that there will be increases in MAT under projected future climatic conditions. The difference between intermediate and present climates is presented in the top left map in **Figure 13.2** and indicates that all Quinaries will experience virtually uniform increases in MAT of approximately 2-3°C over this time 75 year time period.

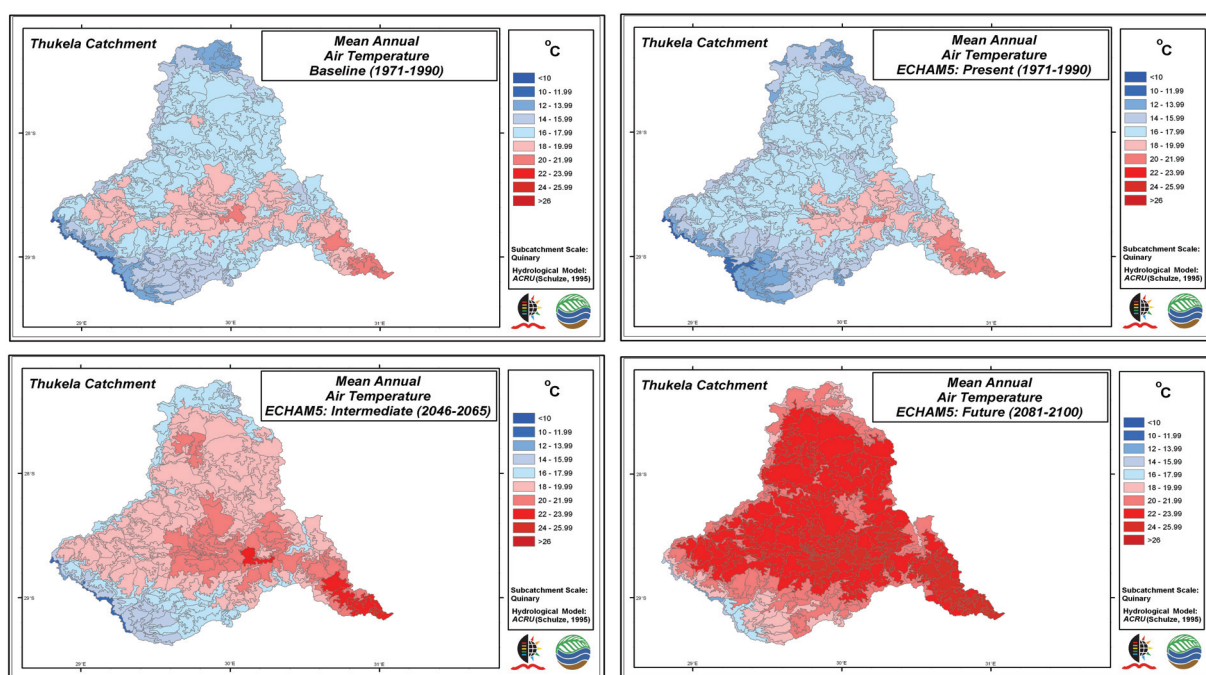


Figure 13.1 Mean annual air temperature per Quinary Catchment in the Thukela for (top left) present baseline climate vs (top right) the present ECHAM5 climate scenario, (bottom left) the intermediate future ECHAM5 and (bottom right) the distant future ECHAM5 climate scenarios

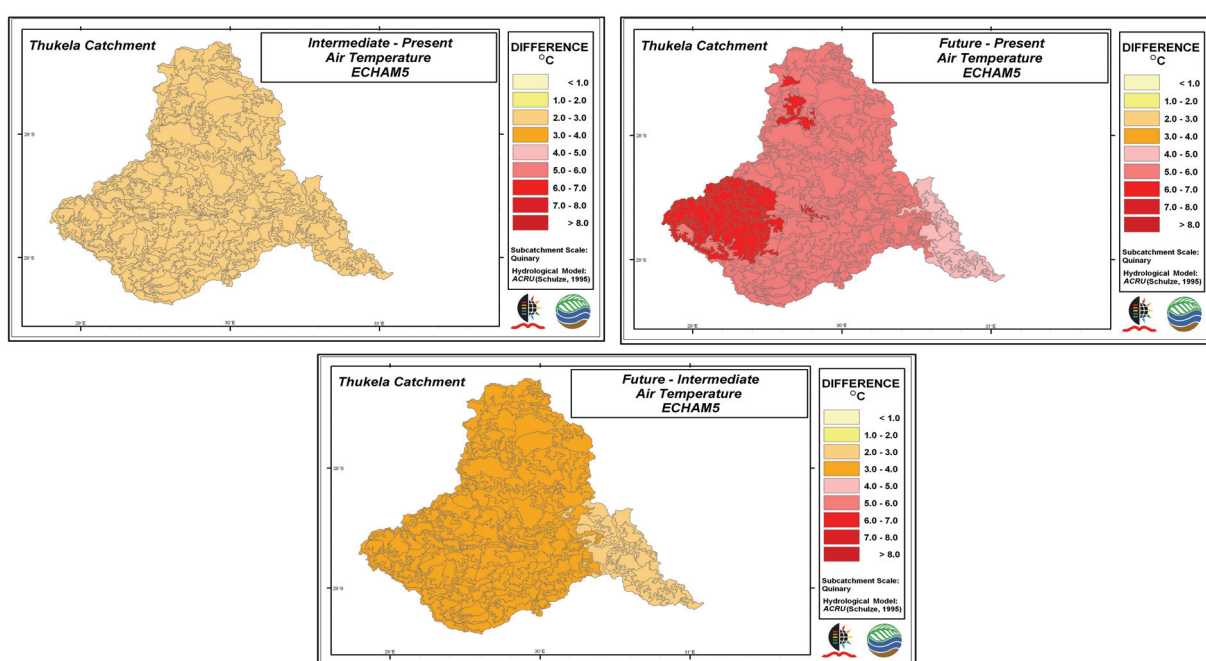


Figure 13.2 Differences in mean annual air temperatures per Quinary Catchment in the Thukela between (top left) the intermediate future and present, (top right) distant future and present and (bottom) distant and intermediate future climate scenarios from the ECHAM5 GCM

The map of distant future minus present MAT (**Figure 13.2** top right) displays the greatest increase in MAT, with the maximum change occurring in northwestern region of the Catchment, where an

increase of around 7°C is projected. This increase could have a dramatic effect on the sensitive mountain ecosystems located in this region. The central parts of the catchment are projected to experience a temperature increase in the region of 5-6°C while the lower parts of the catchment show less change, with a projected increase of 4-5°C. These major increases in MAT are explained by the map of distant minus intermediate future ECHAM5 climate scenario (**Figure 13.2** bottom), with projected increases in MAT for all Quinaries in the Thukela, but with the central areas increasing by 3-4°C over this 35 year period, while the lower reaches show less of a temperature increase, echoing the statement above that the lower reaches are less sensitive to projected climate change.

13.2.3 Projected changes in future means of air temperature for selected months

Figures 13.3 through **13.6** display the results of an analysis of mean air temperature for four cardinal months in the Thukela Catchment performed at Quinary Catchment scale. The top left map in each of these figures displays the historical mean air temperatures for that particular month, the top right map always displays the temperatures from the present ECHAM5 climate scenario for that particular cardinal month, while the bottom maps in each figure display the differences between future ECHAM5 scenarios for mean air temperature for that particular cardinal month, with the intermediate future minus present temperatures displayed in the bottom left map and the distant future minus present temperatures displayed in the bottom right map. This monthly analysis reveals that January (mid-summer; **Figure 13.3**) is the warmest of the four months selected while July (mid-winter) is the coldest, with April (autumn) and October (spring) experiencing mean air temperatures which are similar to one another and which fall between the middle of the two extremes months.

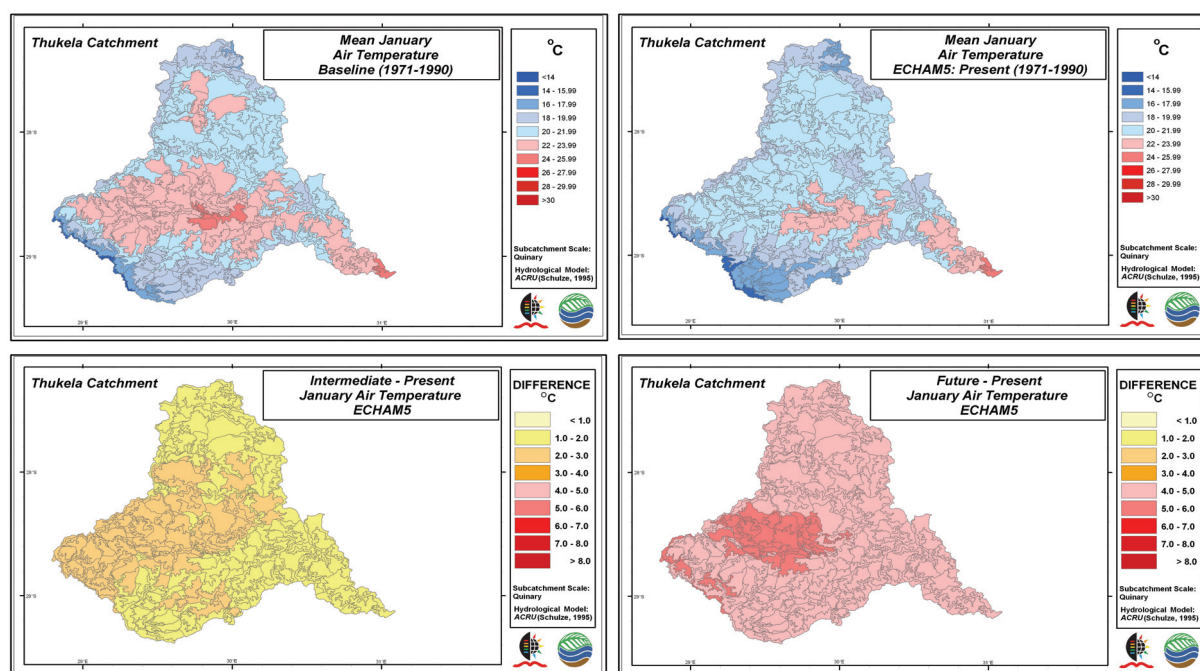


Figure 13.3 Mean January air temperatures in the Thukela Catchment for (top left) present baseline climate vs (top right) present ECHAM5 climate, and differences between projected January intermediate future and present (bottom left), and distant future and present (bottom right) air temperatures

A comparison between present baseline climate (**Figures 13.3-13.6** top left) and present ECHAM5 climate (**Figure 13.3-13.6** top right) indicates that the ECHAM5 GCM is under-simulating mean air temperatures in January (**Figure 13.3**) and October (**Figure 13.6**) by between 0.1 and 3.9°C, particularly in the central and western parts of the Thukela Catchment. Conversely, the comparison between present baseline and present ECHAM5 climates for July indicates that the GCM is, in fact, over-simulating air temperatures for large portions of the catchment while April mean air temperatures (**Figure 13.4**) actually reveal a close correlation between the present historical climate and the present ECHAM5 climate. These results suggest that there are significant intra-annual differences between the historical climate data and the simulated ECHAM5 present climate, and that a simple annual analysis (**Section 13.2.1**) can mask many of these differences.

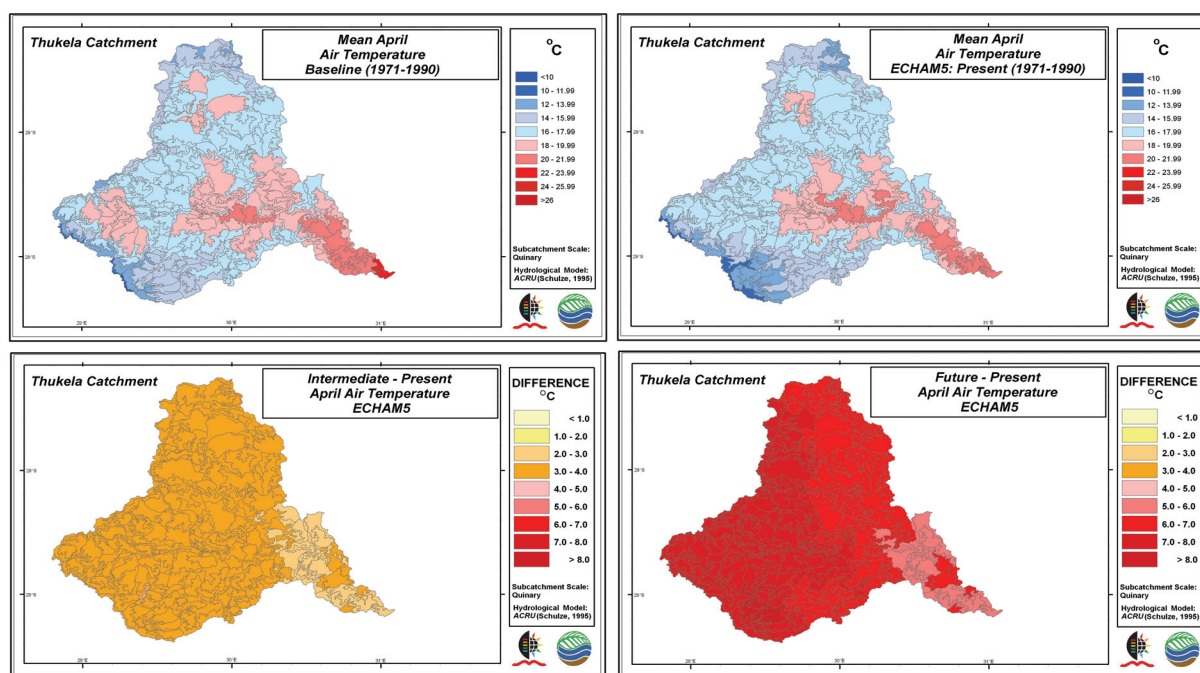


Figure 13.4 Mean April air temperatures in the Thukela Catchment for (top left) present baseline climate vs (top right) present ECHAM5 climate, and differences between projected April intermediate future and present (bottom left), and distant future and present (bottom right) air temperatures

The bottom left map in **Figures 13.3-13.6** displays the differences between the intermediate future and present ECHAM5 climate scenarios for the four cardinal months. All months project that all the Quinaries in the Thukela Catchment will experience an increase in air temperature over this 75 year time period. The months of April, July and October all project increases of between 2 and 4°C in mean air temperature. Furthermore, these months reveal that the lower (eastern) reaches of the Thukela are less prone to projected temperature increases than the central and upper (more western) parts. It is projected that January (**Figure 13.3** bottom left) will experience less of an increase compared to that of the other three selected months, with most of the catchment only experiencing a 1 to 2°C increase in air temperature.

The bottom right map in **Figures 13.3-13.6** illustrates the differences between the more distant future and present ECHAM5 climate scenarios for the four cardinal months. As expected, these maps show a far greater change in mean air temperature over the 110 year period (2081-2100 vs 1971-1990). This set of maps does, however, follow the same trends as those of the intermediate minus

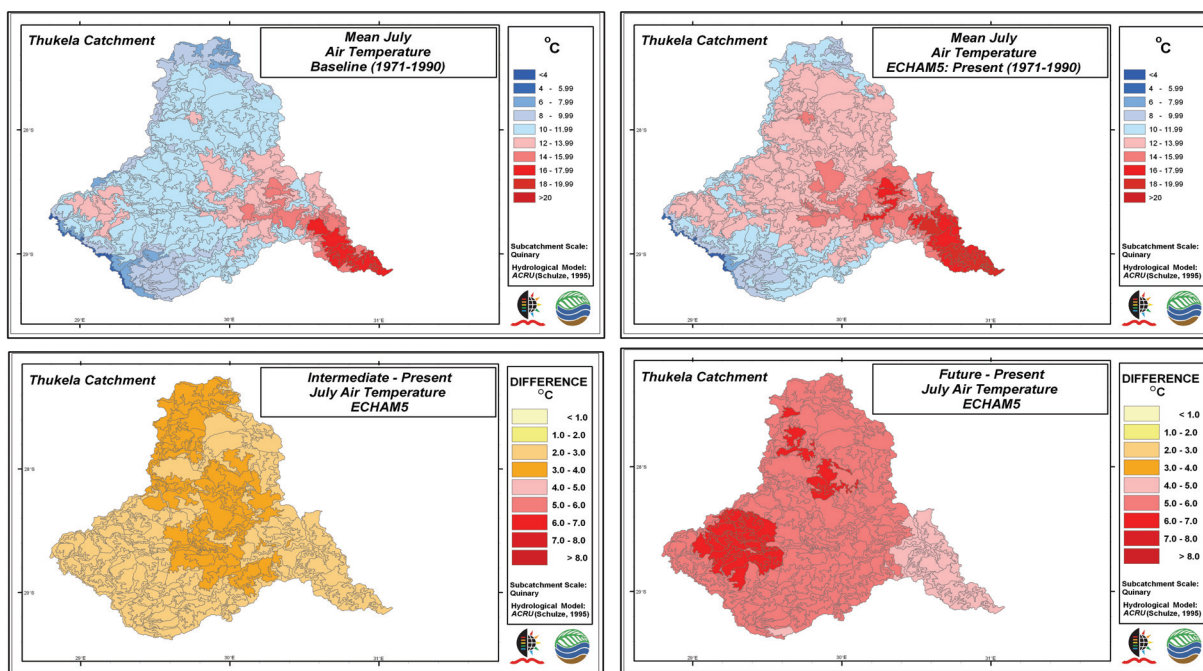


Figure 13.5 Mean July air temperatures in the Thukela Catchment for (top left) present baseline climate vs (top right) present ECHAM5 climate, and differences between projected July intermediate future and present (bottom left), and distant future and present (bottom right) air temperatures

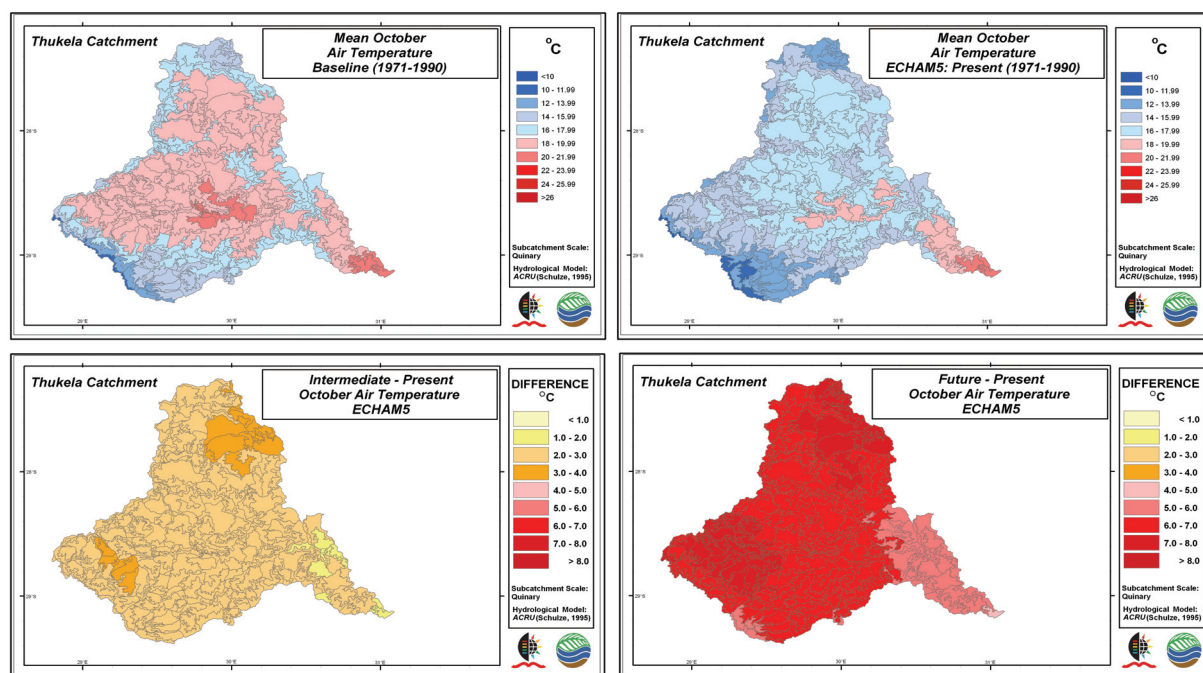


Figure 13.6 Mean October air temperatures in the Thukela Catchment for (top left) present baseline climate vs (top right) present ECHAM5 climate, and differences between projected October intermediate future and present (bottom left), and distant future and present (bottom right) air temperatures

present analysis, with all Quinaries experiencing significant increases in air temperature. Again, air temperature for the month of January shows less of an increase compared to that of the other three selected months. The western Drakensberg appears to be particularly sensitive to a projected change in air temperature, with this region likely to experience increases of up to 8°C for the months of April, July and October according to ECHAM5 climate projections.

13.3 Runoff from Individual Subcatchments

Simulated runoff from individual subcatchments (SIMSQ) is an output from the *ACRU* model and is defined as the sum of stormflows and baseflows, from only the subcatchment in question, excluding any contributions from upstream catchments (Schulze, 1995). The *ACRU* model outputs this variable in millimetre (mm) equivalents and it is subsequently converted to cubic metres (m³) using the subcatchment area. An analysis of individual subcatchment runoff is important because adding accumulated streamflows from upstream can mask the runoff characteristics of the individual subcatchment in question. Furthermore, it is vital in aquatic ecological studies to have an idea of how the individual subcatchment's flows are likely to respond to projected climate change.

Individual subcatchment runoff was generated for the following scenarios (cf. **Chapter 9** for full description):

- Baseline Historical Climate (1971-1990),
- Present GCM Climate (1971-1990),
- Intermediate Future Climate (2046-2065), and a more
- Distant Future Climate (2081-2100).

The analysis was performed at two temporal scales, viz. for annual flows and for those of selected cardinal months (January = summer, April = autumn, July = winter and October = spring). The annual results can be utilised to reveal overall trends for each scenario while the monthly time scale provides a more focused representation in order to determine intra-annual (seasonal) differences. A comparison between the baseline historical scenario and the present scenario is required to judge how well the selected GCM is simulating the present observed climate and, hence, runoff. The analysis of individual subcatchment runoff also includes ratio comparisons between the three ECHAM5 scenarios, viz. intermediate future to present, distant future to present and distant to intermediate future, in order to determine how individual subcatchment runoff is changing from one scenario to the next.

13.3.1 Mean annual runoff from individual subcatchments

Figure 13.7 displays the mean annual runoff from individual subcatchments within the Thukela Catchment for the four scenarios described in **Chapter 9**. When comparing results from present baseline climate (top left) and present ECHAM5 climate (top right), these indicate that ECHAM5 tends to under-simulate annual individual subcatchment runoff, especially in the central and northern areas of the Thukela Catchment. When comparing the ECHAM5 scenarios, results indicate that there will be a marked increase in projected annual subcatchment runoff, with the future scenario (bottom right) showing the greatest change compared to that of the present ECHAM5 climate (top right).

13.3.2 Ratios of future annual runoff from individual subcatchments

Figure 13.8 displays the ratios between the three ECHAM 5 scenarios for mean annual runoff from the individual subcatchments making up the Thukela Catchment. All maps indicate that there will be an increase in simulated individual catchment runoff under projected future conditions. The ratio map

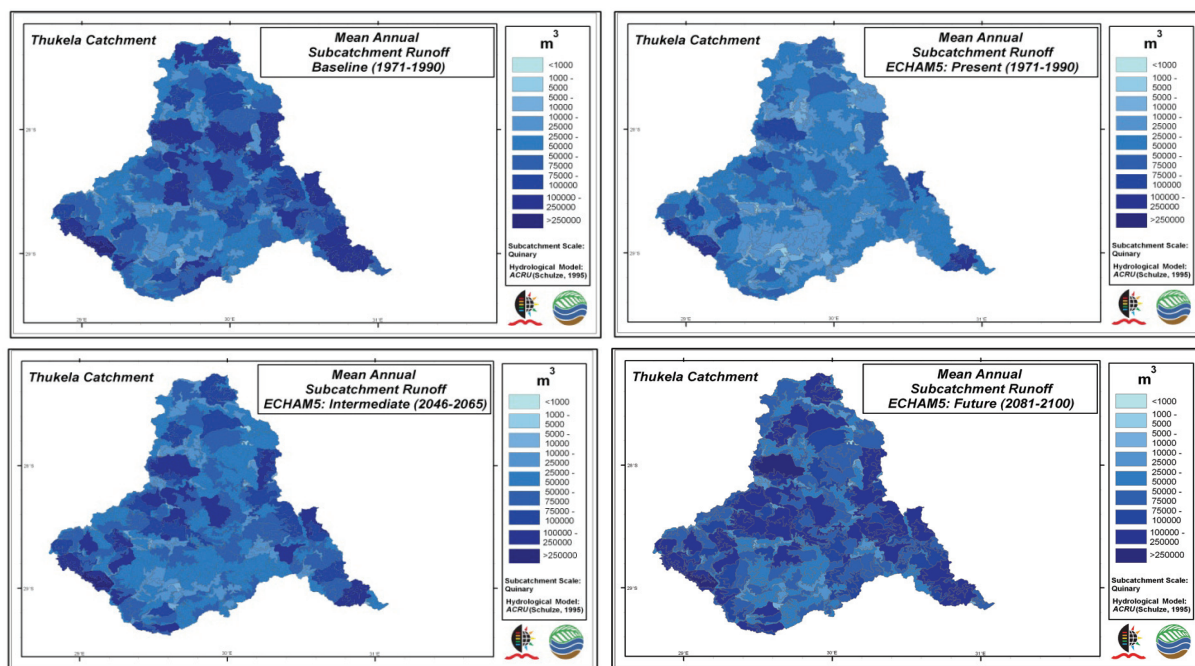


Figure 13.7 Simulated mean annual subcatchment runoff for (top left) present baseline climate, (top right) present ECHAM5 climate, (bottom left) the intermediate future ECHAM5 climate and (bottom right) the distant future ECHAM5 climate

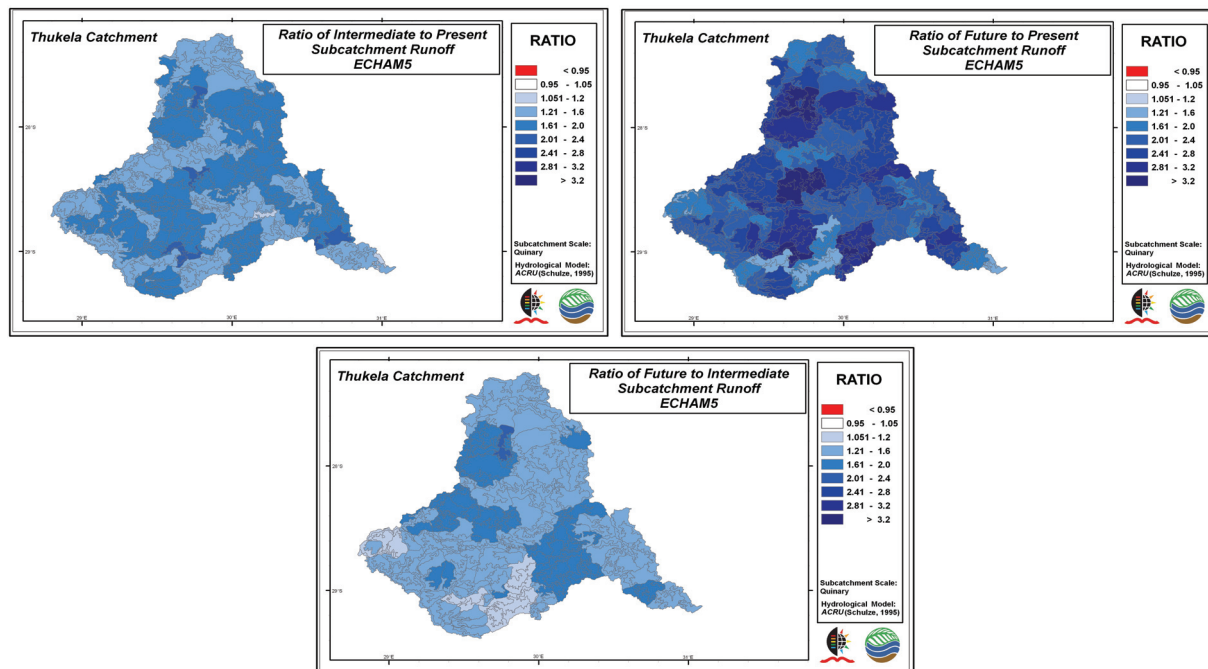


Figure 13.8 Ratios of future annual runoff from individual subcatchments for (top left) the intermediate future to present, (top right) distant future to present and (bottom) distant to intermediate future ECHAM5 climate scenarios

of distant future to present ECHAM5 climates (top right) illustrates the greatest change in individual subcatchment runoff, with most Quinaries showing an increase of between 2 and 3 times compared to that of the simulated runoff from the present ECHAM5 climate. The other two ratio comparisons between intermediate future and present (top left) and distant and intermediate futures (bottom) also indicate increases in individual catchment runoff, but to a lesser degree, with average increases by a factor of 1.2 and 1.6. The reason for the distant future to present ratio map (top left) showing the greatest change is that the present climate scenario time period (1971-1990) and the distant future climate scenario time period (2081-2100) are 110 years apart from the commencement of their respective simulation periods compared with the difference between the intermediate and future climate scenarios only being 35 years from the start of their respective simulation periods.

13.3.3 Monthly runoff and future ratios of monthly runoff from individual subcatchments

When comparing simulated mean January individual subcatchment runoff from present ECHAM5 climate (**Figure 13.9** top right) with that from the present baseline climate (**Figure 13.9** top left) it may be seen that the ECHAM5 GCM is under-simulating runoff by a large amount. This under-simulation is particularly noticeable in the central and northeasterly parts of the Thukela Catchment. Scrutiny of daily rainfall files from the ECHAM5 GCM indicates that this GCM appears to be under-simulating large flood producing events, often probably in the form of more local convective storms, which are common in mid-summer in this region of South Africa. The January ratio map for runoff from intermediate future to present projected climates (**Figure 13.9** bottom left) indicates that a large majority of the Quinary subcatchments in the Thukela Catchment will experience an increase in runoff. A small number of Quinaries nevertheless display no change or even a slight decrease in individual catchment runoff. However, the overall trend seems to indicate an increase in runoff for January of between 1.05 and 1.50 times. This trend continues when comparing the runoff generated

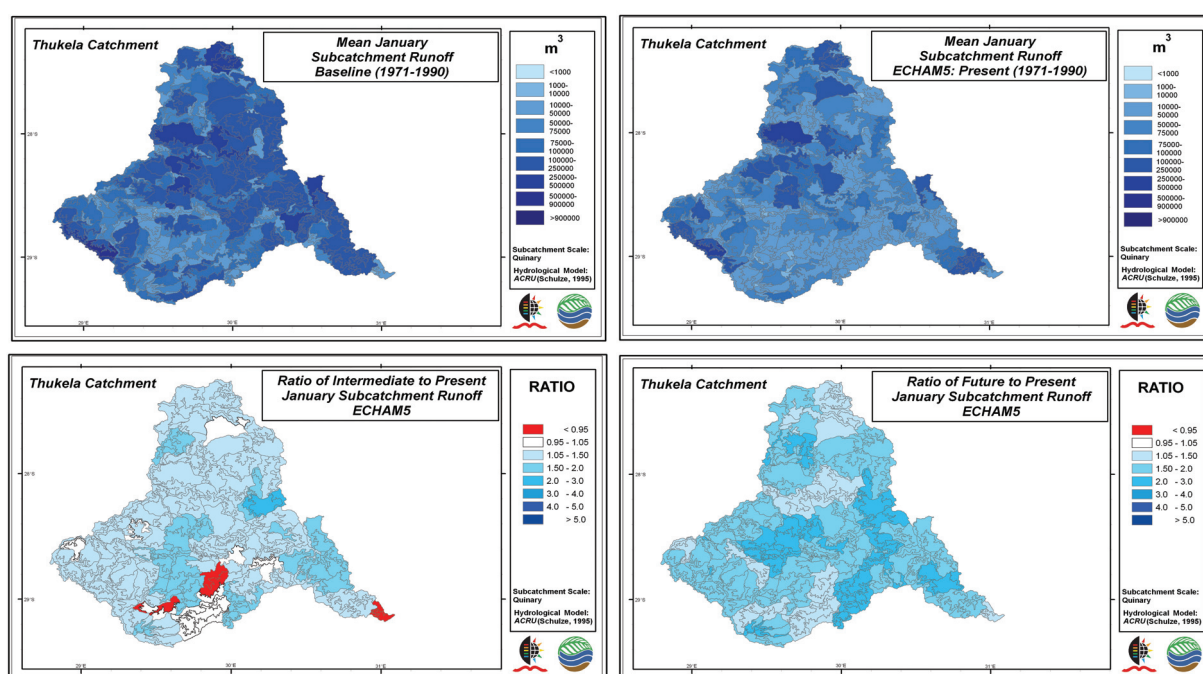


Figure 13.9 Simulated mean January subcatchment runoff for (top left) present baseline climate vs (top right) present ECHAM5 climate, and ratios of January runoff from individual subcatchments for (bottom left) intermediate future to present and (bottom right) distant future to present climate scenarios

from distant future to present ECHAM5 January climate scenarios (**Figure 13.9** bottom right), where all Quinaries in the Thukela show a definite increase in individual subcatchment runoff of between 1.50 and 2.00 times.

When comparing simulated mean April individual subcatchment runoff for present ECHAM5 climate (**Figure 13.10** top right) with that from the present baseline climate (**Figure 13.10** top left), it may be seen that runoff generated by this GCM shows a close correlation with that generated from the historical climate. This strong correlation indicates that the GCM simulation appears to be performing better for this time of the year compared to that of the January analysis. This may either signify that the GCM is able to simulate smaller (often frontal) and more general rainfall events more accurately than in mid-summer, and thus performs better in the drier months of the year, or that runoff more likely takes the form of baseflow rather than convective event driven stormflow. The April ratio maps for the projected future climates (**Figure 13.10** bottom left and right) both show an overall increase in individual catchment runoff, with the distant future to present comparison illustrating the greatest changes with some Quinaries showing a 5-fold increase in runoff.

The comparison between simulated mean July individual catchment runoff for present ECHAM5 climate (**Figure 13.11** top right) and the present baseline climate (**Figure 13.11** top left) indicates that the GCM has an almost perfect correspondence with the historical climate. This again echoes the point that ECHAM5 performs well in the drier parts of the year. The intermediate future to present ratio map for July (**Figure 13.11** bottom left) shows that almost all Quinaries in the Thukela will experience an increase in individual catchment runoff in the intermediate future, with the central part of the catchment showing an increase of between 200 and 300%. The distant future to present ratio map (**Figure 13.11** bottom right) also has a wetting trend, but to a far greater degree with a number of Quinaries in the Northern reaches of the Buffalo experiencing a 5-fold increase.

When comparing the mean October present baseline climate (**Figure 13.12** top left) with the mean October present ECHAM5 climate (**Figure 13.12** top right) the results indicate that ECHAM5 is tending to under-simulate rainfall events which is leading to an under-simulation in the individual catchment runoff. Like January, October is a month when rainfall is relatively high in the Thukela and this causes a decrease in correlation between the historical climate and the simulated climate from the GCM. The intermediate future to present ratio map for October (**Figure 13.12** bottom left) points to an overall increase in individual catchment runoff, with the majority Quinaries in the Thukela experiencing an increase of between 105 and 150%. The distant future to present ratio map for October (**Figure 13.12** bottom right) also reveals a strong wetting pattern in the distant future with the Buffalo subcatchment being particularly sensitive to projected climate change.

13.4 Accumulated Catchment Streamflows

Accumulated streamflow is an output from the *ACRU* model and is defined as the total summed streamflow from a (sub)catchment which also includes any contributions from upstream catchments (Schulze, 1995). The *ACRU* model outputs this variable in millimetre (mm) equivalents and it is subsequently converted to cubic metres (m³) using the (sub) catchment area. An analysis of accumulated catchment streamflow is important in water temperature studies not only because it is the integral of all flows which were generated upstream of the point of interest, but also because it is used in the determination of the volume related water temperature of the entire Catchment.

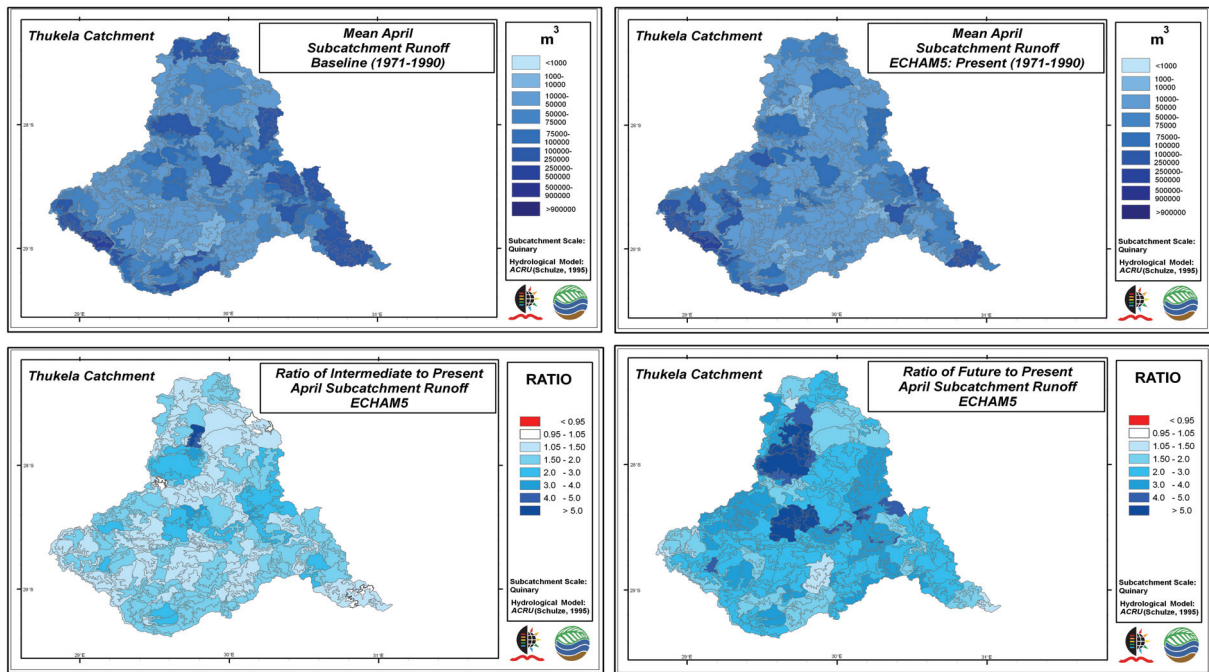


Figure 13.10 Simulated mean April subcatchment runoff for (top left) present baseline climate vs (top right) present ECHAM5 climate, and ratios of April runoff from individual subcatchments for (bottom left) intermediate future to present and (bottom right) distant future to present climate scenarios

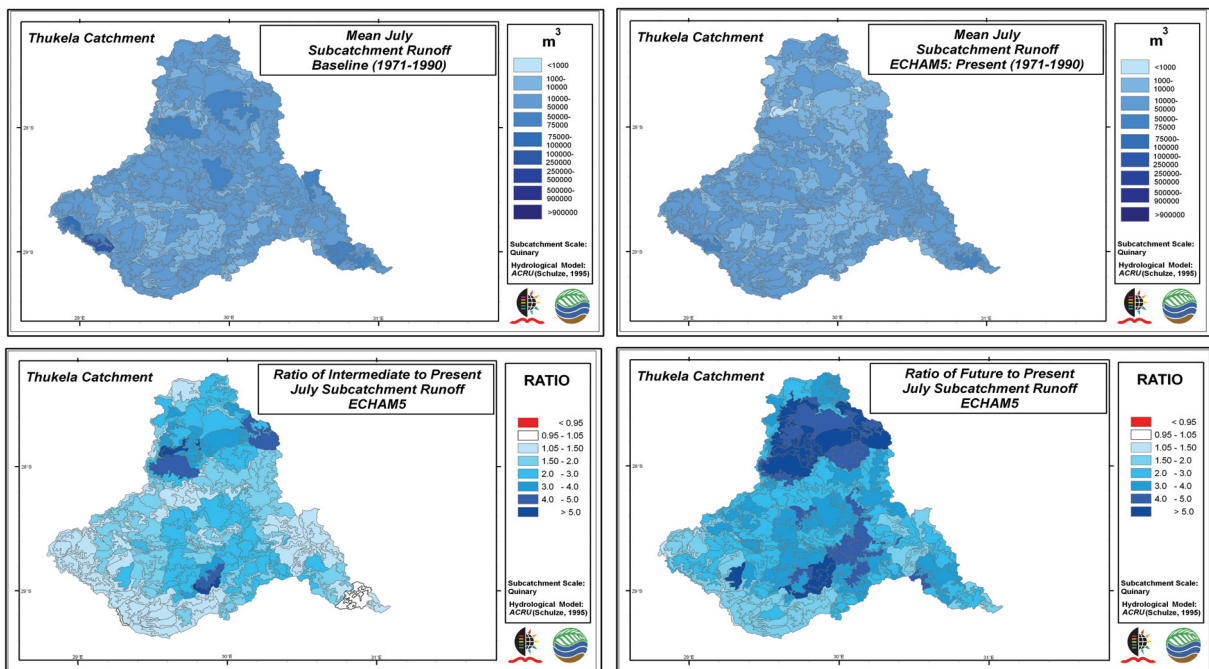


Figure 13.11 Simulated mean July subcatchment runoff for (top left) present baseline climate vs (top right) present ECHAM5 climate and ratios of July runoff from individual subcatchments for (bottom left) intermediate future to present and (bottom right) distant future to present climate scenarios

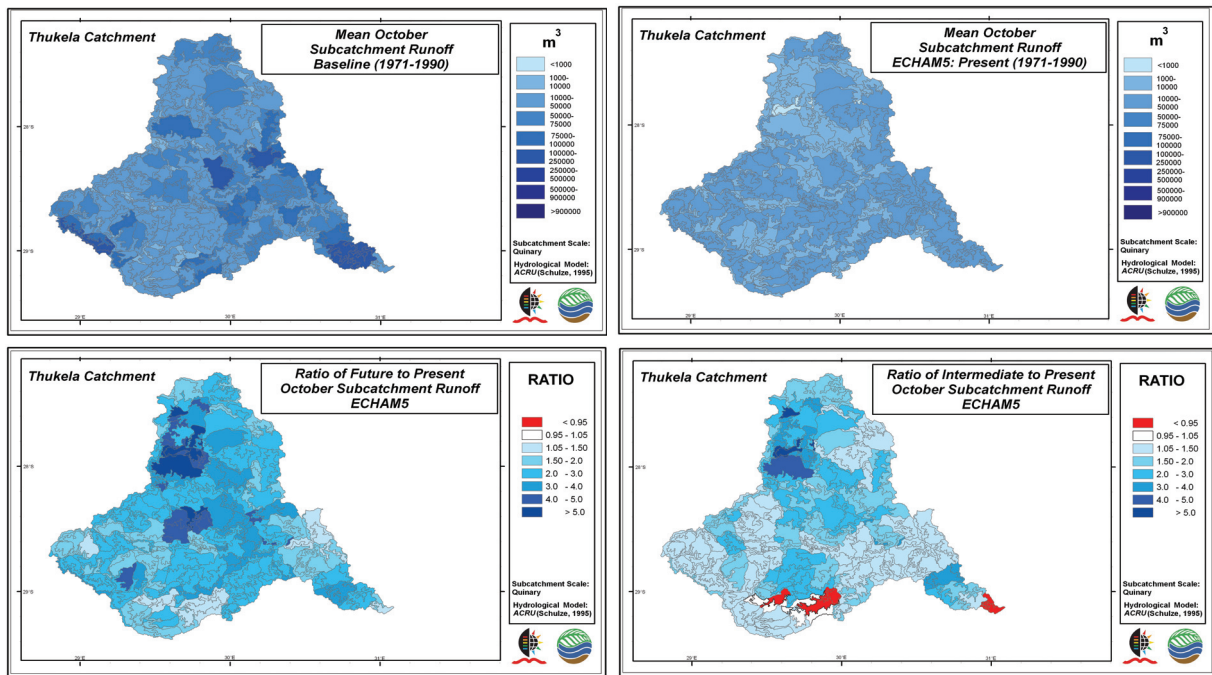


Figure 13.12 Simulated mean October subcatchment runoff for (top left) present baseline climate vs (top right) present ECHAM5 climate and ratios of October runoff from individual subcatchments for (bottom left) intermediate future to present and (bottom right) distant future to present climate scenarios

13.4.1 Mean annual accumulated catchment streamflows

Figure 13.13 displays the mean annual accumulated streamflows per Quinary Catchment for the entire Thukela Catchment, for the four climate scenarios described in **Chapter 9**. When comparing accumulated streamflows generated from present baseline climate (**Figure 13.13** top left) with those from the present ECHAM5 climate scenario (**Figure 13.13** top right), the results indicate that the simulations are generally closely correlated, with both these scenarios clearly showing the accumulations of streamflows in the major tributaries in Thukela Catchment with the same/similar darker blue colours on the respective maps. There is, however, a slight under-simulation of generated streamflows in the central parts of the Thukela when using the present ECHAM5 GCM climate as input. Although the wide range within the class intervals makes interpretations difficult, a comparison between the accumulated streamflows derived from the intermediate and more distant future ECHAM5 scenarios indicates a wetting trend over time, particularly over the central Thukela.

13.4.2 Ratio comparisons of the future to present mean annual accumulated catchment streamflows

Figure 13.14 displays the ratio comparisons for the Thukela Catchment of mean annual accumulated streamflows between the three ECHAM5 climate scenarios. All maps indicate that there will be increases in accumulated streamflows under projected future climate conditions. The ratio map of distant future to present ECHAM5 climates (top left) displays the greatest change in accumulated streamflows, with most Quinaries showing a doubling and even tripling compared to that simulated from the present ECHAM5 climate scenario. The other two ratio comparisons between the intermediate future and present (top left), and the more distant and intermediate futures (bottom), also point to increases in accumulated streamflows, but to a lesser degree, with average increases by a factor of 1.2 to 1.6.

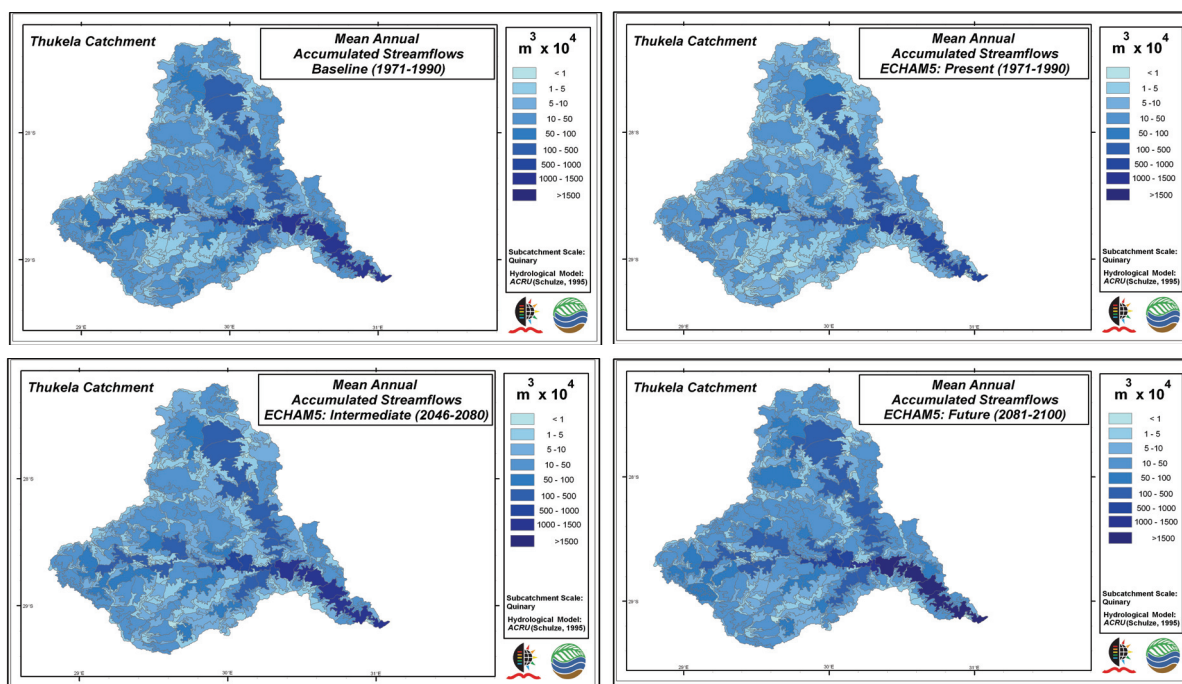


Figure 13.13 Simulated mean annual accumulated streamflows per Quinary Catchment in the Thukela generated from (top left) present baseline climate vs (top right) the present ECHAM5 climate scenario, (bottom left) from the intermediate future ECHAM5 and (bottom right) the distant future ECHAM5 climate scenario

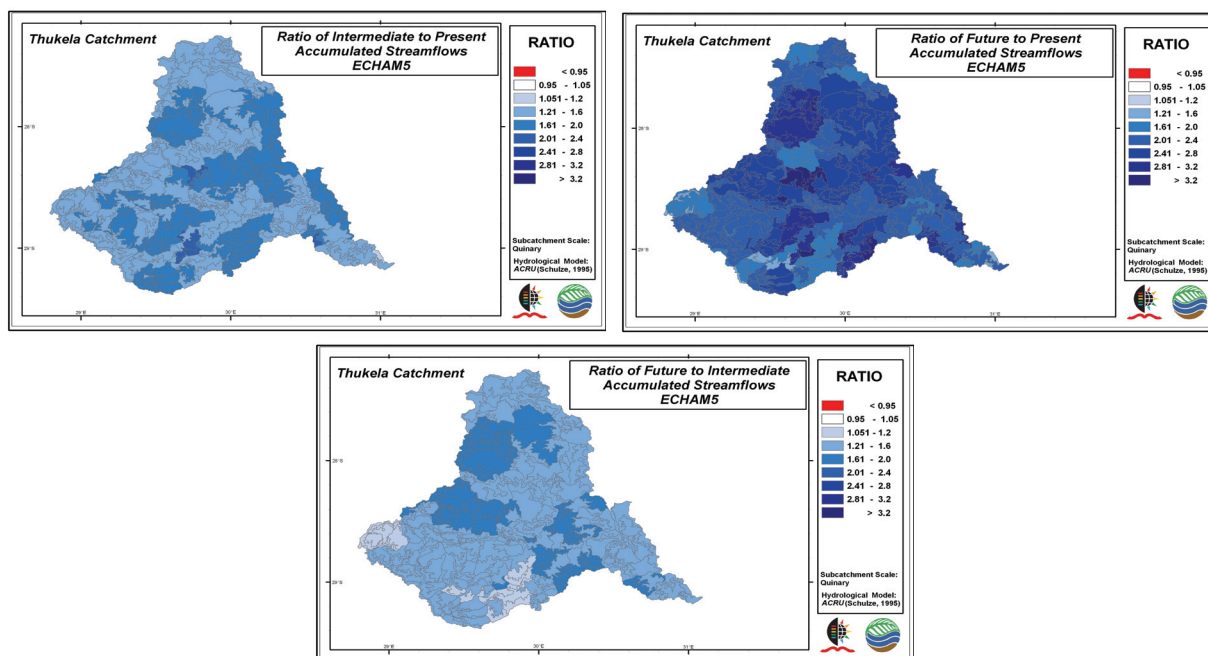


Figure 13.14 Ratios of mean annual accumulated streamflows from (top left) intermediate future to present, (top right) distant future to present and (bottom) distant to intermediate future ECHAM5 climate scenarios

13.4.3 Projected changes in future means of accumulated catchment streamflows for selected months

An analysis of the four selected cardinal months shows that, as expected in a summer rainfall region, January displays the highest accumulated streamflows, July experiences the lowest streamflows while April and October shows similar spatial patterns of streamflows typical of transitional seasons. An evaluation of monthly accumulated streamflows generated from the baseline present climate and the ECHAM5 present climate (**Figures 13.15-13.18**) indicates that there is generally a good correlation between these two scenarios, however, with the present ECHAM5 climate tending to under-simulate accumulated streamflows in all four selected months, most noticeably in October.

A ratio analysis between the three ECHAM5 climate scenarios for each of the four cardinal months was also performed for the accumulated streamflows (**Figures 13.15-13.18** bottom left and right). An overall examination of each of the cardinal months reveals an increase in accumulated streamflows over time for all future climate scenarios. However, a few Quinaries in the southwestern corner of the Thukela experience no significant changes in volumes, and even in a decrease in accumulated streamflows for the months of January and October, but this going against the overall trend of streamflow increases. The intermediate future to present ratio map for January (**Figure 13.15** bottom left) suggests that the mid-summer season is, in relative terms, less sensitive to changes in accumulated streamflows under conditions of projected climate change compared to the three months representing the other seasons. The ratio change in accumulated streamflows for most Quinaries is generally between 1.05 and 1.50 for January, while the other three cardinal months in the non-rainy season project somewhat higher ratios of between 1.50 and 2.00, indicative of higher contributions from baseflows.

The bottom right maps in **Figures 13.15 to 13.18** illustrate the differences between the more distant future and present ECHAM5 climate scenarios for the four cardinal months. As expected, these maps show far greater ratio changes in accumulated streamflows than the intermediate future to present maps. Again January (**Figure 13.15** bottom right) seems to be relatively less sensitive to projected climate change. July (**Figure 13.17** bottom right) shows a large ratio change with the upper Buffalo tributary of the Thukela Catchment seeming to be particularly sensitive, with some Quinaries experiencing an increase of between 4 and 5 times compared to present accumulated streamflow volumes. April and October (**Figures 13.16 and 13.18** bottom right) project similar ratio increases of between 2 and 3 times the present accumulated streamflow volumes. As already explained before, these large relative increases are hypothesised to be due to enhanced baseflows in the non-rainy seasons which result from significant recharge to the groundwater zone in the rainy season.

13.5 Water Temperature Index for Individual Subcatchments

The Water Temperature Index (WTI) for individual subcatchments is equal to the product of the daily maximum water temperature in °C (cf. **Chapter 10**) and the simulated daily runoff (m³) for a particular subcatchment. The analysis of individual subcatchment WTIs is restricted to a ratio comparison between the three ECHAM5 scenarios because the actual WTI value is, in itself, a relatively meaningless ones. The individual subcatchment WTI reveals how the combination of water temperature and runoff are likely to respond to projected climate change, at the level of a single subcatchment. An analysis of individual subcatchment WTI is important because accumulating WTIs from upstream can mask the runoff and water temperature characteristics of the individual subcatchment in question.

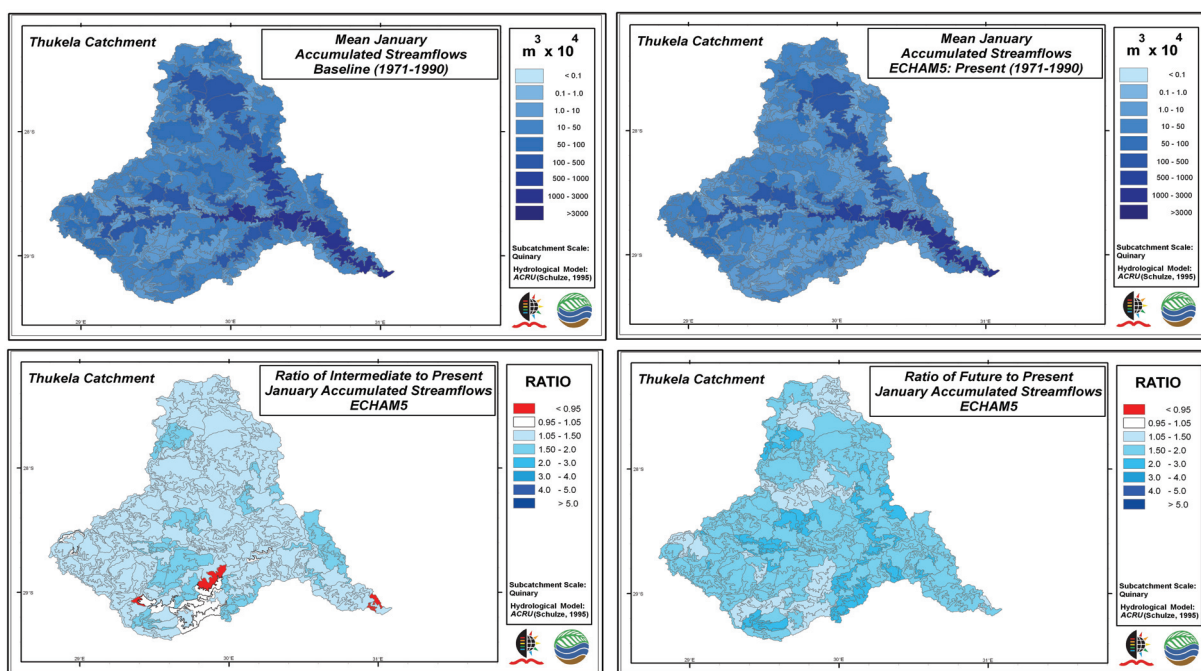


Figure 13.15 Simulated January means of accumulated streamflows generated from (top left) present baseline climate vs (top right) the present ECHAM5 climate scenario, and ratios of simulated January accumulated streamflows for (bottom left) intermediate future to present and (bottom right) distant future to present climate scenarios

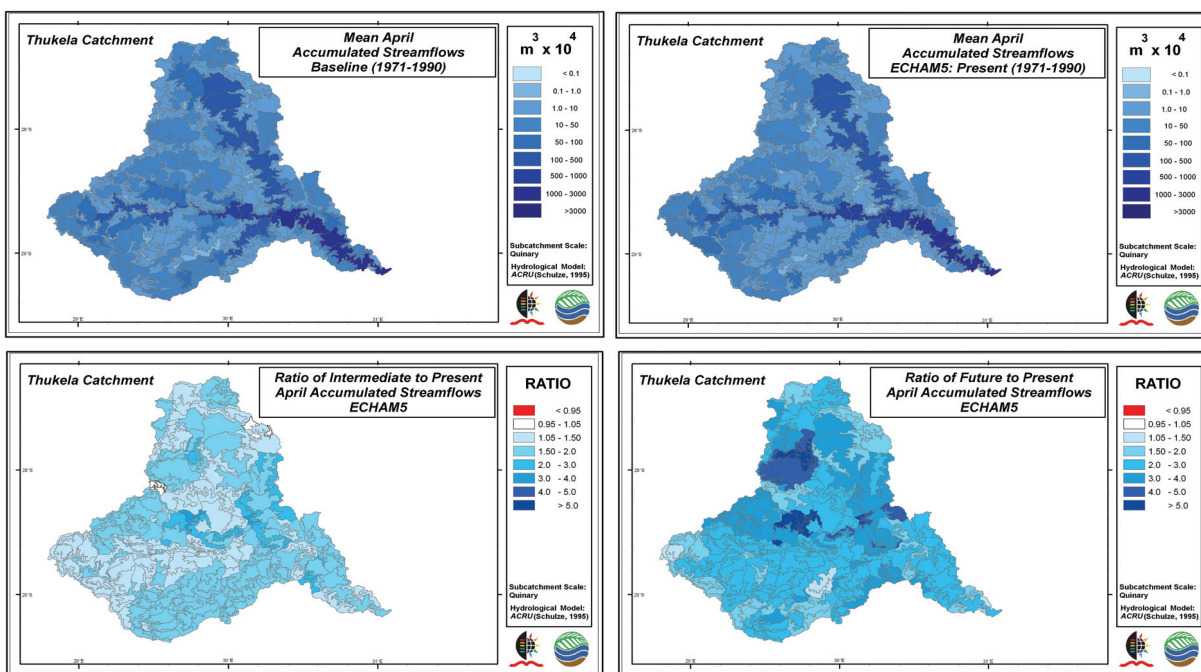


Figure 13.16 Simulated April means of accumulated streamflows generated from (top left) present baseline climate vs (top right) the present ECHAM5 climate scenario, and ratios of April accumulated streamflows for (bottom left) intermediate future to present and (bottom right) distant future to present climate scenarios

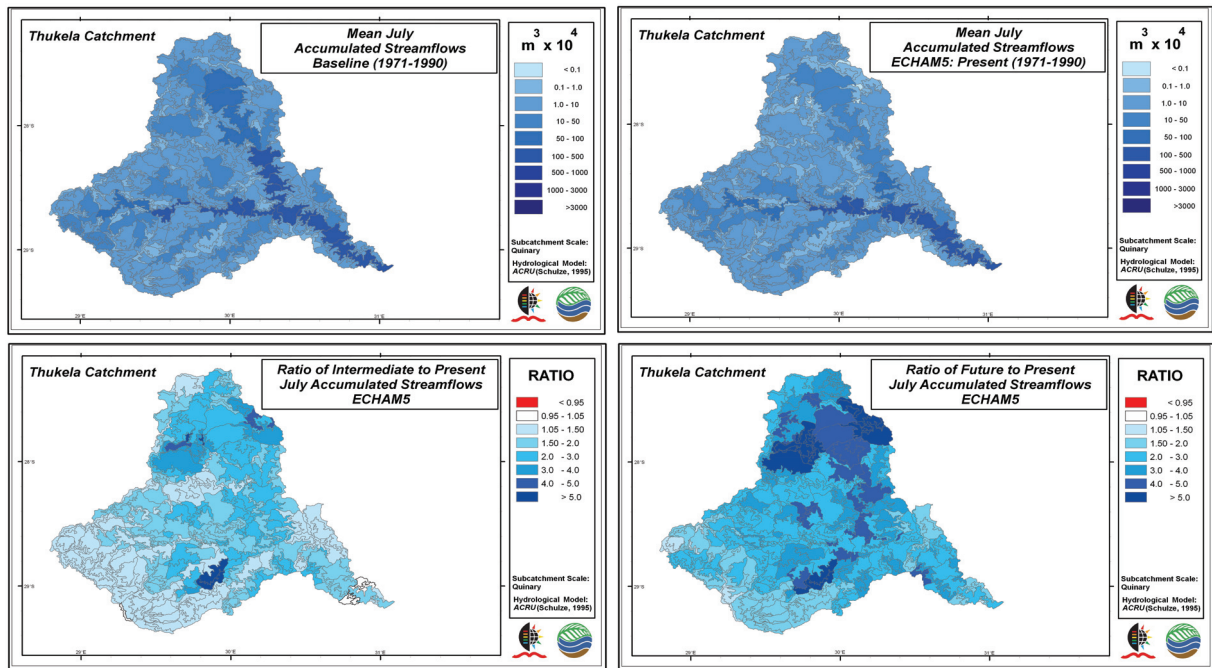


Figure 13.17 Simulated July means of accumulated streamflows generated from (top left) present baseline climate vs (top right) the present ECHAM5 climate scenario, and ratios of July accumulated streamflows for (bottom left) intermediate future to present and (bottom right) distant future to present climate scenarios

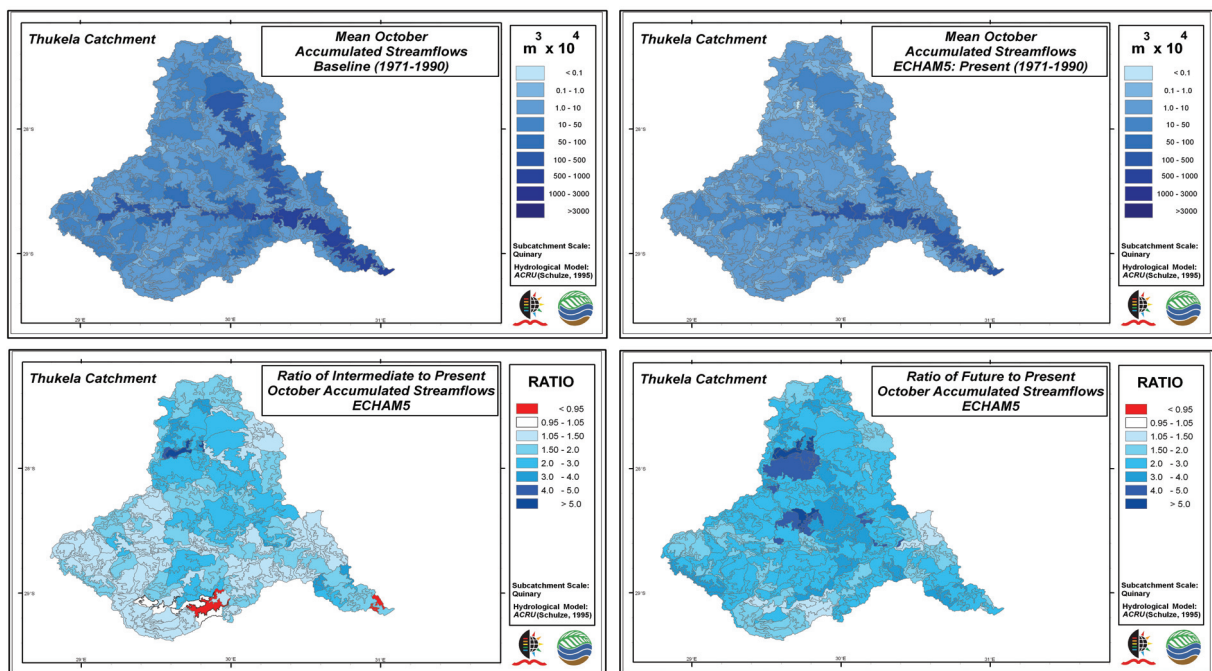


Figure 13.18 Simulated October means of accumulated streamflows generated from (top left) present baseline climate vs (top right) the present ECHAM5 climate scenario, and ratios of October accumulated streamflows for (bottom left) intermediate future to present and (bottom right) distant future to present climate scenarios

13.5.1 Ratios of future annual water temperature indexes for individual subcatchments

Figure 13.19 displays the ratios between the three ECHAM5 scenarios for mean annual individual subcatchment WTIs. All maps indicate that there will be an increase in the simulated individual subcatchment WTI under projected future climate conditions. The ratio comparisons between intermediate future and present (**Figure 13.19** top left) and distant and intermediate future climates (**Figure 13.19** bottom) show similar results and indicate increases in individual catchment WTIs, with average increases by a factor of 1.5 and 2. The ratio map of distant future to present ECHAM5 climates (**Figure 13.19** top right) illustrates the greatest change in individual subcatchment WTIs, as expected, with some Quinaries showing an increase by a factor of 4 and more compared to those of the simulated WTI from the present ECHAM5 climate.

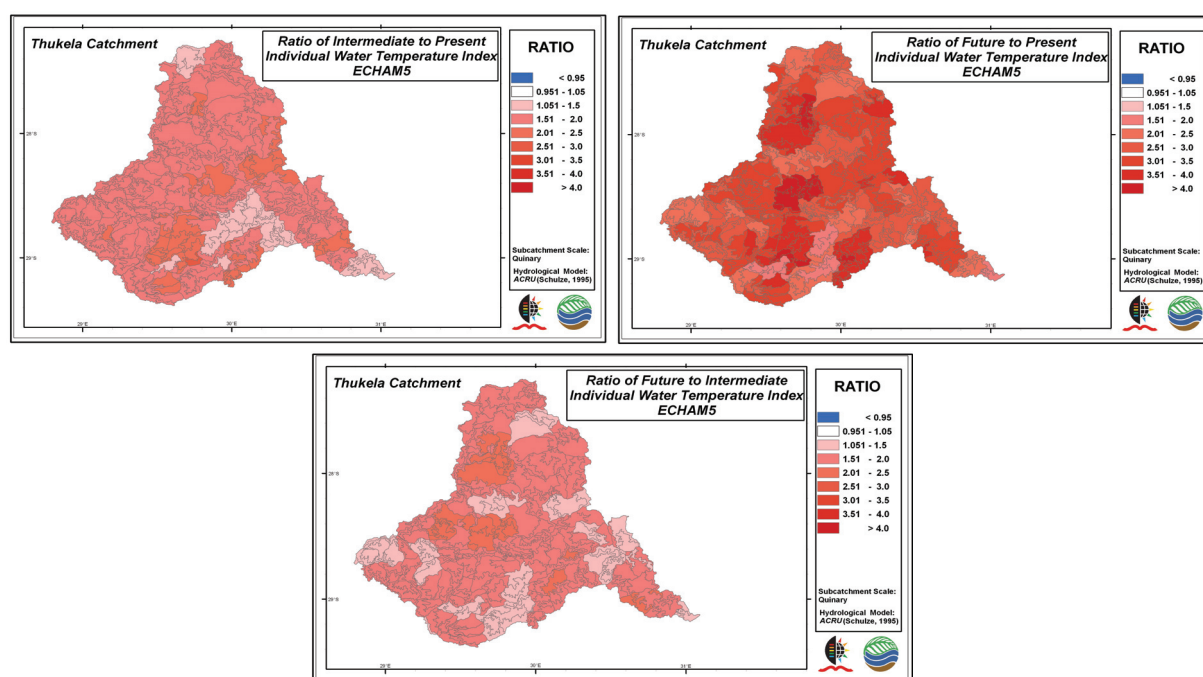


Figure 13.19 Ratios of future annual Water Temperature Indexes from individual subcatchments for (top left) intermediate future to present, (top right) distant future to present and (bottom) distant to intermediate future ECHAM5 climate scenarios

13.5.2 Ratios of future monthly water temperature index for individual subcatchments

A ratio analysis between the three ECHAM5 scenarios was performed for individual subcatchment WTIs for the four cardinal months. All months show an overall increase in individual catchment WTI over time, with the distant future to present scenario experiencing the greatest increase. This overall increase over time is expected owing to the fact that individual catchment WTI is, ultimately, based on air temperature (**Section 13.2**) and individual subcatchment runoff (**Section 13.3**) and in the Thukela Catchment both of these variables are predicted to increase with projected climate change. The month of January, for all ratio comparisons, tends to be relatively less sensitive to projected climate change compared to the other three cardinal months. The intermediate future to present maps (**Figures 13.20-13.23** top left) all project an increase in individual catchment WTIs, but reveal some intra-annual differences. The January intermediate future to present map (**Figure 13.20** top left) shows a virtually uniform increase in individual subcatchment WTIs by a factor of between 1.05 and 1.5. The increases are projected to be higher for April (**Figure 13.21** top left), with most

Quinaries experiencing increases of between 1.5 and 2.0. July and October show similar results for the intermediate future to present analysis (**Figures 13.22 and 13.23** top left), with both these transitional months revealing a strong increase in individual subcatchment WTIs, particularly in the Buffalo tributary catchment where Quinaries are projected to experience an increase by a factor of between 3 and 4 compared to that of the ECHAM5 simulated present climate.

The distant future to present maps (**Figures 13.20-13.23** top right) also project an increase in individual catchment WTIs for all months, but by an even greater magnitude compared to the other ratio maps. Again January (**Figure 13.20** top right) tends to be less sensitive to projected climate change in relative terms, with individual subcatchment WTIs for the middle Quinaries increasing by a factor of between 2 and 3 for the distant future to present ratio analysis. April, July and October maps (**Figures 13.21-13.23** top right) show similar results to each other with these months experiencing large increases in individual subcatchment WTIs by factors of up to 5 in certain Quinaries.

The distant to intermediate future maps (**Figures 13.20-13.23** bottom) show similar results to the intermediate to present analysis in regard to the magnitude of change for individual subcatchment WTIs. January and July (**Figures 13.20 and 13.22** bottom) show an almost uniform increase in individual subcatchment WTIs between the future and intermediate scenarios. Individual subcatchment WTIs for January are projected to increase by between 1.05 and 1.50 times, while this factor increases to 1.50 and 2.0 for most Quinaries in July. The ratio changes for April (**Figure 13.21** bottom) between the distant and intermediate future scenarios tend to be highly variable, with some Quinaries projected to even decrease, while others are projected to increase their WTI by a factor of between 3.0 and 4.0. Finally, October (**Figure 13.23** bottom) shows an overall increase in individual subcatchment WTI, with the middle Quinaries expected to increase by a factor between 1.50 and 2.0 and the western Drakensberg Quinaries increasing by approximately 2.5 times over this time period.

13.6 Water Temperature Index of Accumulated Flows

Water temperature is dynamic as water is always mixing within the river channel as well with water from joining tributaries. This, however, complicates water temperature modelling. In order to account for this mixing the accumulated Water Temperature Index (WTI) was developed. The accumulated WTI uses individual subcatchment WTIs (**Section 13.5**), but accumulates these down the catchment in a similar way that accumulated streamflow is calculated (**Section 13.4**). The accumulated WTI, or simply WTI, creates a weighting system at the exit of two Quinaries or a confluence of rivers in order to give the larger flow more influence on the combined WTI. This accumulation continues longitudinally down a river system, and consequently the water of the Quinary entering the ocean will have been influenced by all the upstream catchments. The analysis of accumulated WTIs is restricted to a ratio comparison between the three ECHAM5 scenarios since the actual WTI value *per se* is a relatively meaningless one.

13.6.1 Ratios of future annual accumulated water temperature index

An annual ratio analysis between the three ECHAM5 scenarios was performed for the accumulated WTIs. All maps indicate an increase in the accumulated WTI over time (**Figure 13.24**). The intermediate future to present climate ratio map (**Figure 13.24** top left) and that of the distant to intermediate future climates (**Figure 13.24** bottom) both show similar results, with most Quinaries experiencing an increase by a factor of 1.5 to 2.0. The map showing the ratios between the distant future and present ECHAM5 climates (**Figure 13.24** top right) contains the greatest increase in accumulated WTIs, as expected, with most of the Quinaries' WTIs increasing between 2.5 and 3.5 times compared to those of the accumulated WTIs from the present ECHAM5 climate.

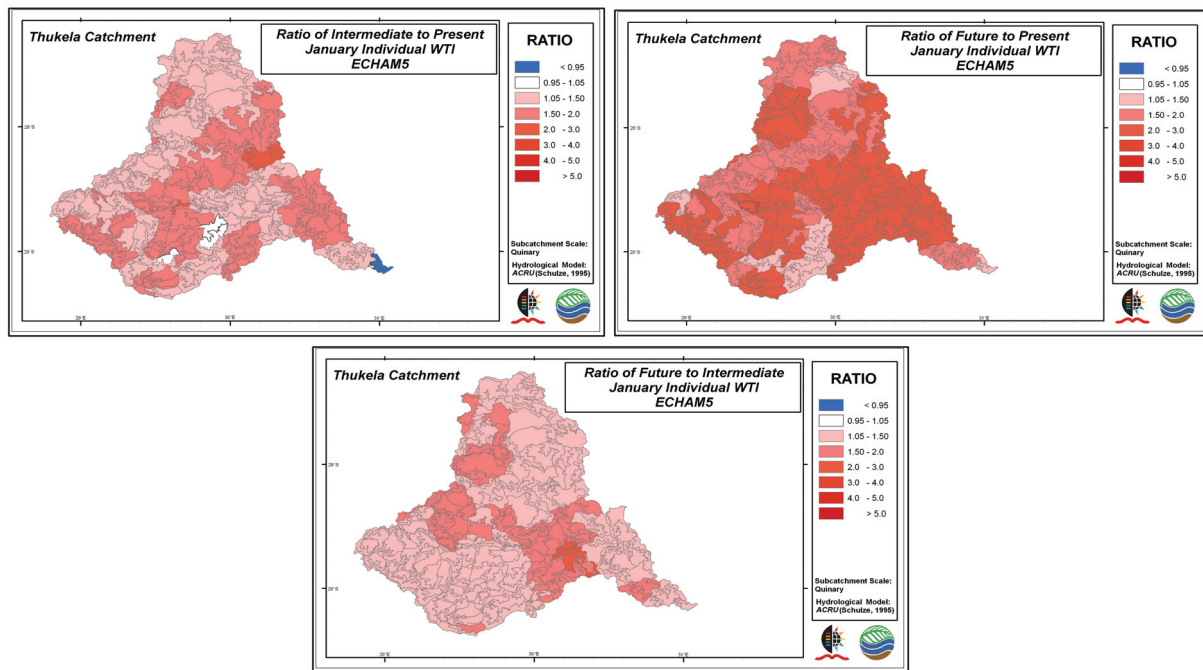


Figure 13.20 Ratios of January Water Temperature Indexes from individual subcatchments for (top left) intermediate future to present, (top right) distant future to present and (bottom) distant to intermediate future ECHAM5 climate scenarios

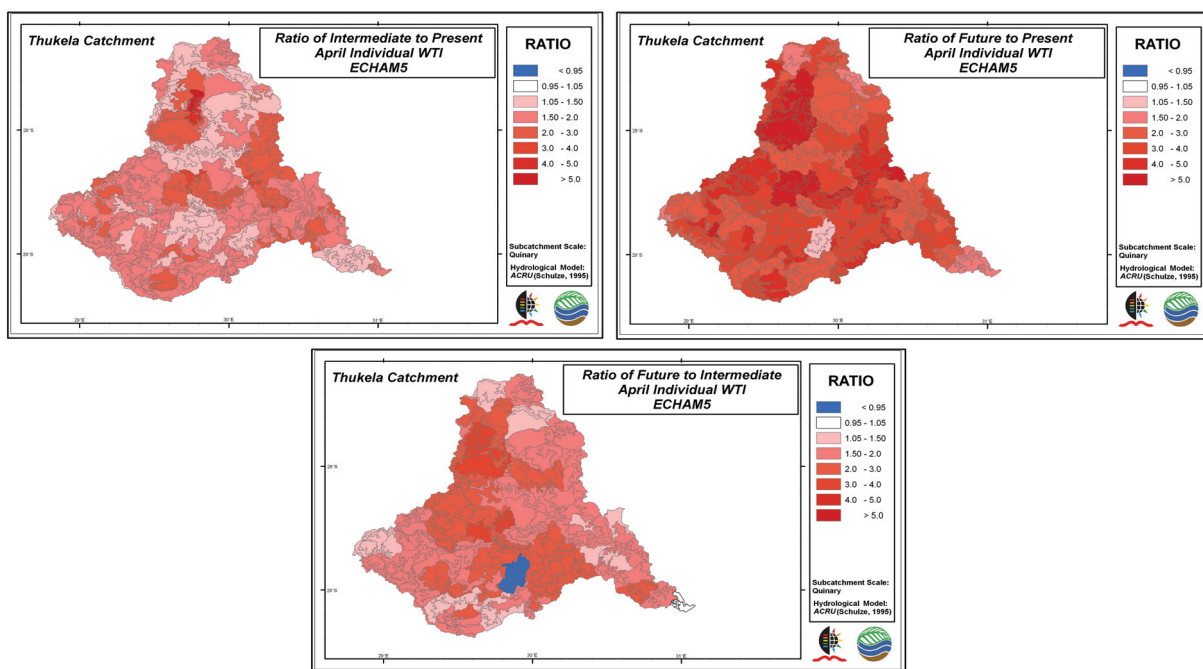


Figure 13.21 Ratios of April water temperature indexes from individual subcatchments for (top left) intermediate future to present, (top right) distant future to present and (bottom) distant to intermediate future ECHAM5 climate scenarios

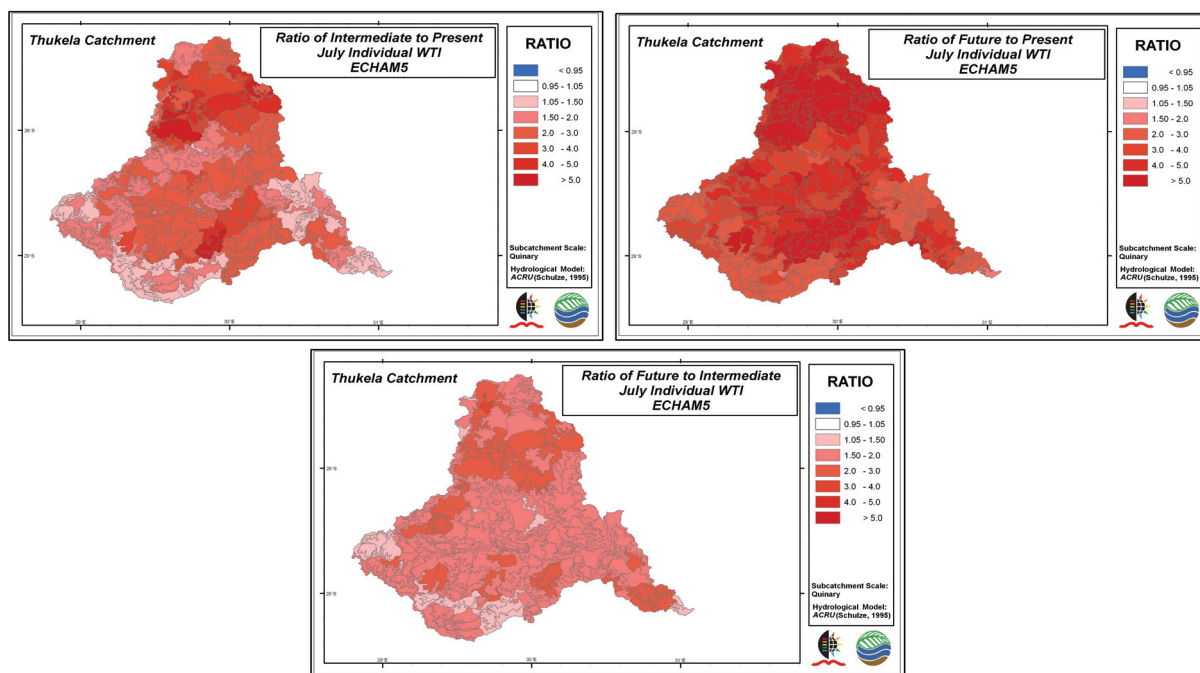


Figure 13.22 Ratios of July water temperature indexes from individual subcatchments for (top left) intermediate future to present, (top right) distant future to present and (bottom) distant to intermediate future ECHAM5 climate scenarios

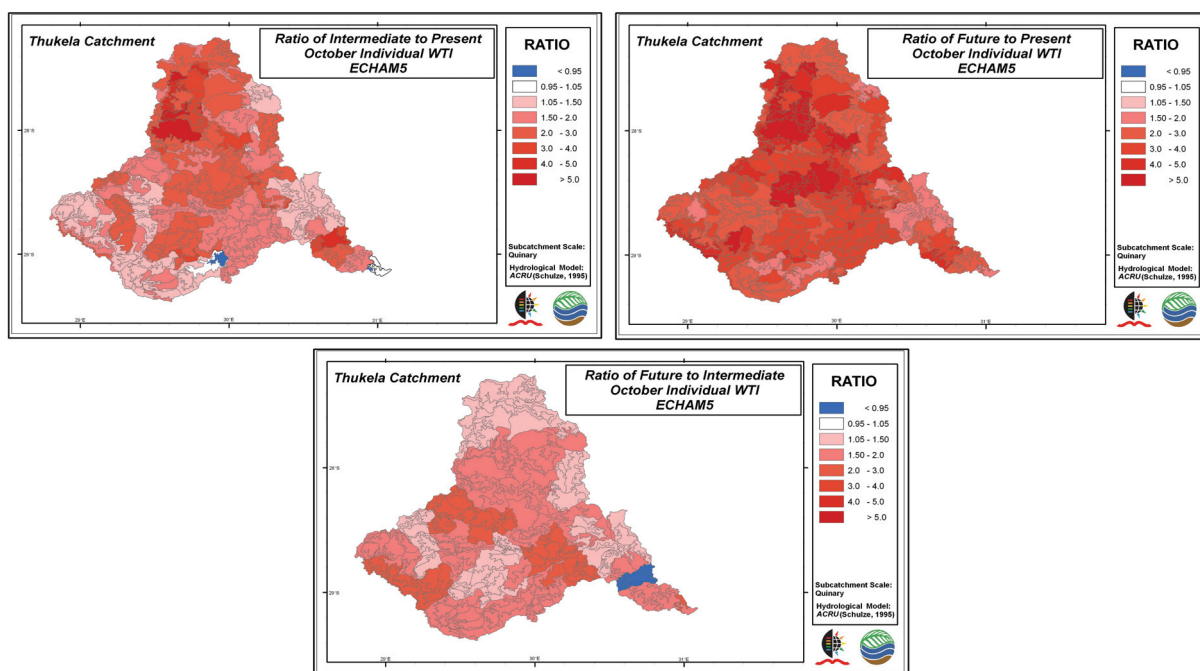


Figure 13.23 Ratios of October water temperature indexes from individual subcatchments for (top left) intermediate future to present, (top right) distant future to present and (bottom) distant to intermediate future ECHAM5 climate scenarios

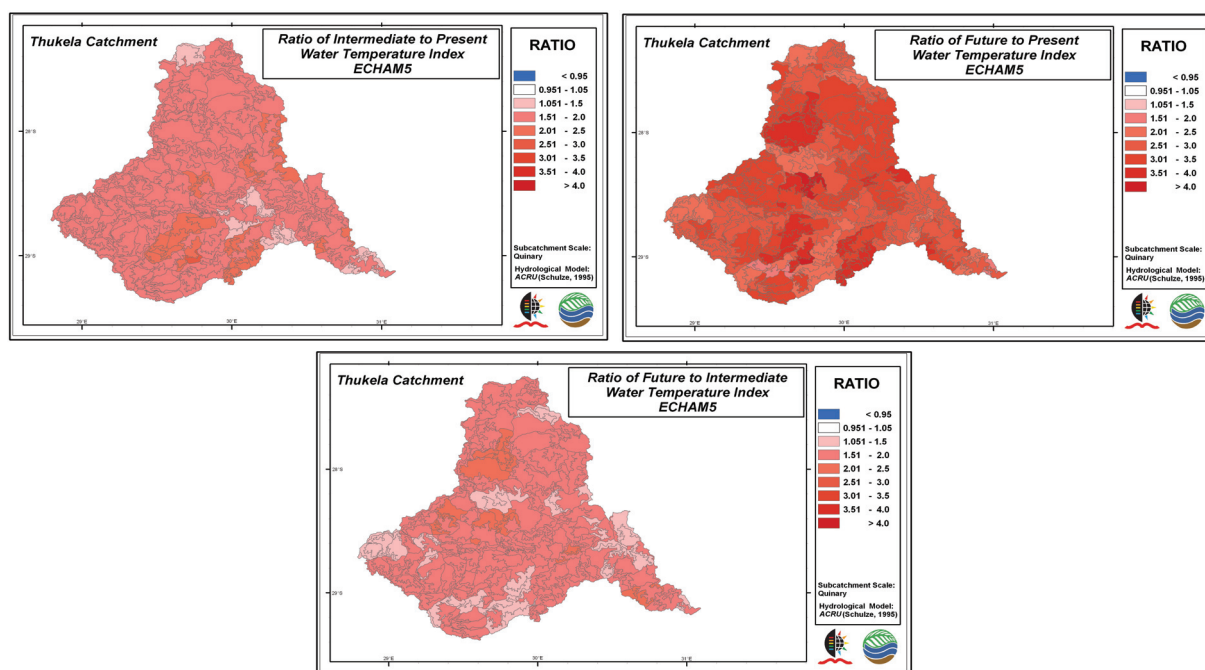


Figure 13.24 Ratios of annual accumulated Water Temperature Indexes for (top left) intermediate future to present, (top right) distant future to present and (bottom) distant to intermediate future ECHAM5 climate scenarios

13.6.2 Ratios of future accumulated water temperature index for selected months

A ratio analysis of the four cardinal months was performed for the accumulated WTI using the three ECHAM5 scenarios (**Figures 13.25-13.28**). An overall assessment shows an increase in accumulated WTI over time for all scenarios and in all four months. Like individual subcatchment WTIs, the increase in accumulated WTIs is to be expected since accumulated WTIs are ultimately based on air temperature (**Section 13.2**) and accumulated streamflows (**Section 13.4**), both of which are projected to increase in the Thukela Catchment with future climates. A small number of Quinaries do, however, display a zero change in volume or even in a decrease in accumulated streamflows for the months of January, April and October in the southwestern corner and near the mouth of the Thukela, but this goes against the overall trend.

The intermediate future to present ratio map for January (**Figure 13.25** top left) suggests that January is less sensitive to changes in accumulated WTI under conditions of projected climate change compared to the other cardinal months. The ratio change in accumulated WTI, for most Quinaries, is around 1.05-1.50 for January while the other three cardinal months project a more mixed and variable increase in magnitude. The month of July (**Figure 13.27** top left) seems to be more sensitive to projected climate change over this time period, especially in the upper regions of the Buffalo Catchment where accumulated WTI is projected to increase by a factor of between 2.0 and 3.0.

The top right map for **Figures 13.25-13.28** illustrates the ratio changes between the future and present ECHAM5 climate scenarios for the four cardinal months. As expected, this map shows a far greater change in accumulated WTI compared to the intermediate to present and future to intermediate ratio maps. Again the month of January (**Figure 13.25** top right) seems to be less

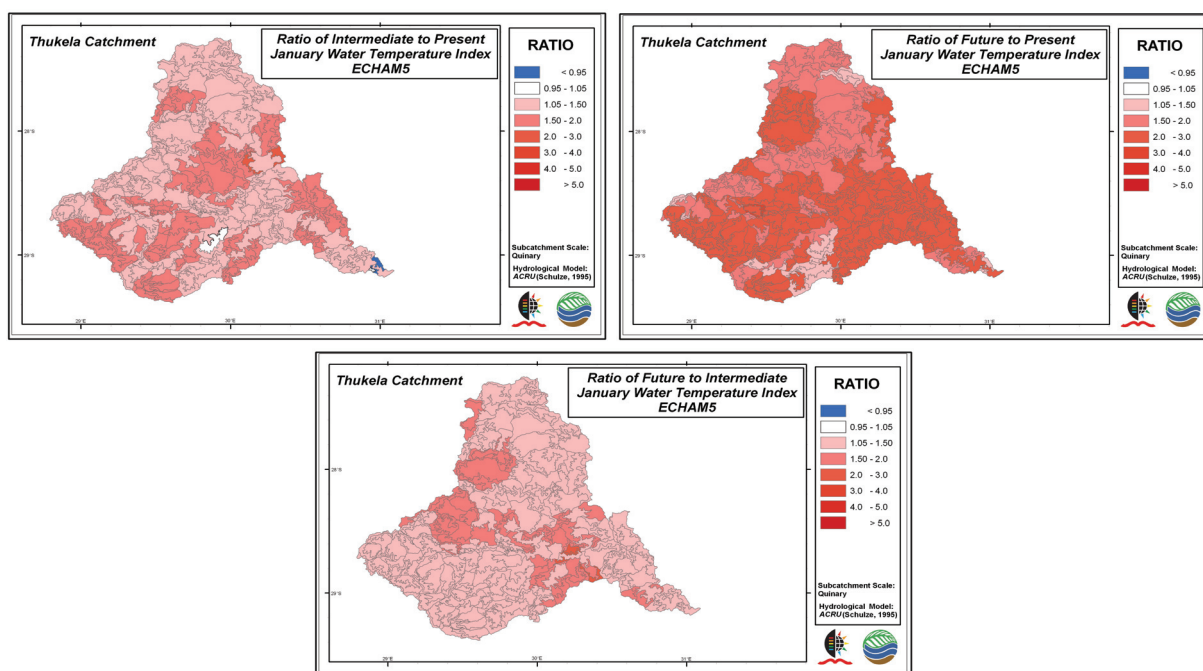


Figure 13.25 Ratios of the January accumulated Water Temperature Index for (top left) intermediate future to present, (top right) distant future to present and (bottom) distant to intermediate future ECHAM5 climate scenarios

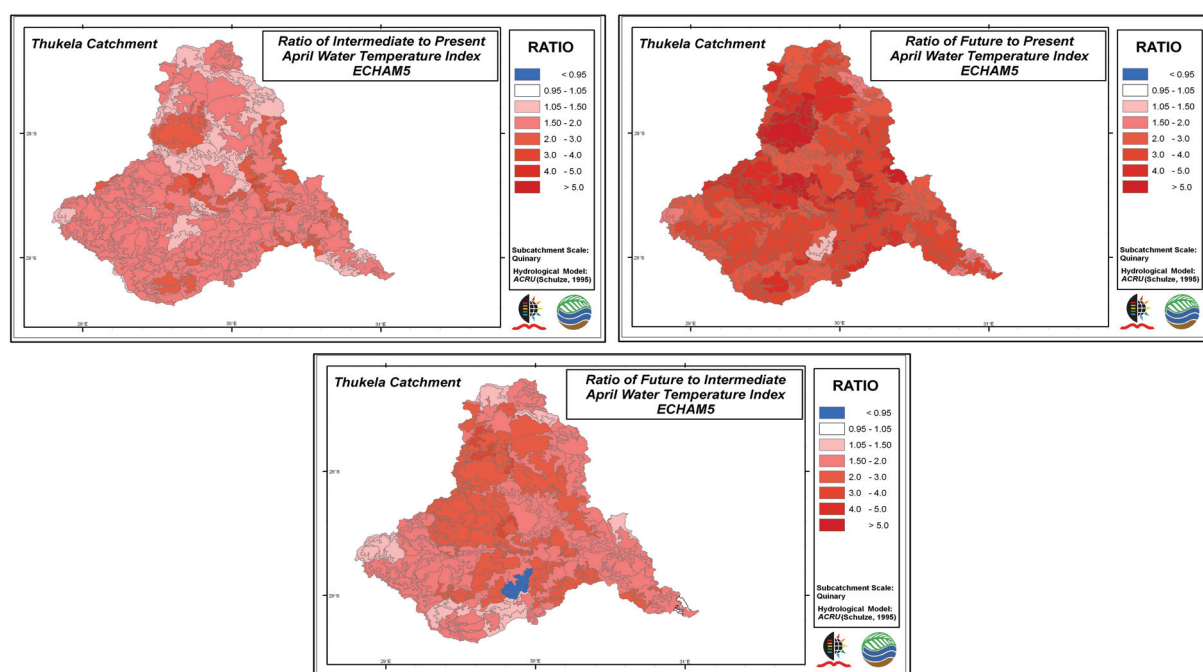


Figure 13.26 Ratios of the April accumulated water temperature index for (top left) intermediate future to present, (top right) distant future to present and (bottom) distant to intermediate future ECHAM5 climate scenarios

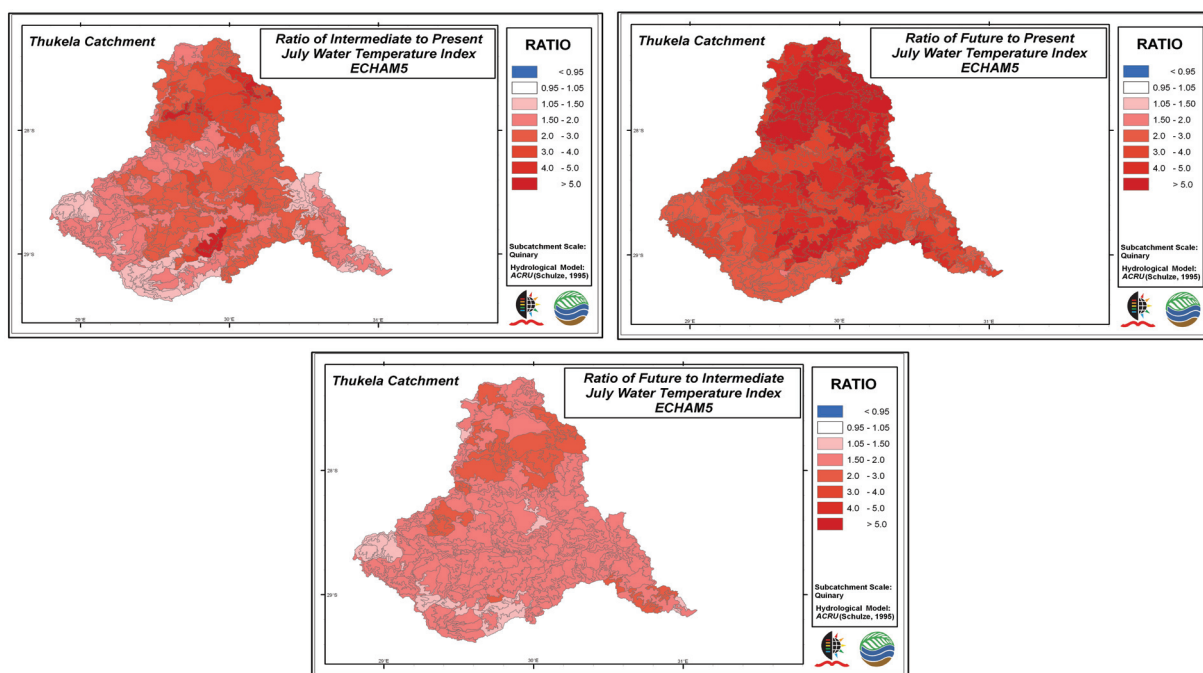


Figure 13.27 Ratios of the July accumulated water temperature index for (top left) intermediate future to present, (top right) distant future to present and (bottom) distant to intermediate future ECHAM5 climate scenarios

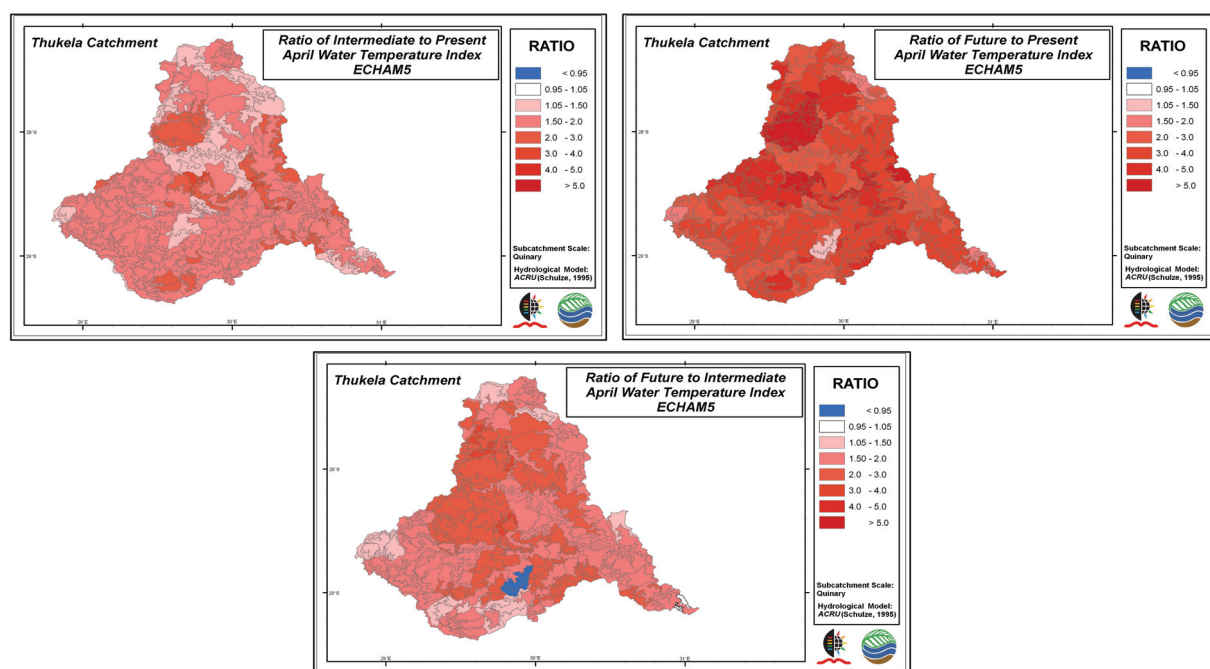


Figure 13.28 Ratios of the October accumulated water temperature index for (top left) intermediate future to present, (top right) distant future to present and (bottom) distant to intermediate future ECHAM5 climate scenarios

sensitive to projected climate change, with most Quinaries experiencing an increase in accumulated WTI by a factor of between 1.50 and 3.0. The months of April, July and October (**Figures 13.26-13.28** top right) all show a strong increasing trend for accumulated WTI over this time period. The month of July seems to be particularly sensitive, with some Quinaries in the upper Buffalo Catchment experiencing an increase by a factor of between 4 and 5 compared to present accumulated WTI. April and October (**Figure 13.26** and **13.28** bottom right) project similar ratio increases of between 2 and 3 times the present accumulated WTI over the remaining parts of the Thukela Catchment.

The bottom map for **Figures 13.25-13.28** illustrates the ratio changes between the distant and intermediate future ECHAM5 climate scenarios for the four cardinal months. January (**Figure 13.25**) has an almost uniform increase in accumulated WTI with a ratio of between 1.05 and 1.50 for all the Thukela Quinaries. July (**Figure 13.27**) also projects a virtually uniform increase in accumulated WTI, but at a greater magnitude of change for this ratio analysis, with most Quinaries experiencing a doubling in accumulated WTI over this time period. April and October (**Figures 13.26** and **13.28**) reveal a large amount of variability in the magnitude of increase for accumulated WTI, but overall the WTI is projected to increase from the intermediate to more distant future ECHAM5 climate scenarios, as temperatures continue to rise and rainfall, hence streamflow, is projected to continue increasing.

13.7 Mixed Maximum Water Temperature

The mixed maximum water temperature (MMWT) is calculated by dividing the accumulated Water Temperature Index (WTI) on a specific day by the accumulated streamflow of that day for a particular Quinary Catchment (**Section 13.6**). MMWT is therefore essentially a weighted value, expressed in degree Celsius, based on computations of maximum water temperature (**Chapter 9**). The MMWT is an important indicator for aquatic ecosystems and is in a workable and understandable unit.

13.7.1 Mean annual mixed maximum water temperatures

An evaluation of mean annual MMWTs derived from the baseline present climate and those computed from the ECHAM5 present climate scenario indicates that both show the same overall trends (**Figure 13.29** top left vs top right). The mean annual MMWT is relatively low at +/- 11°C in the high altitude areas, especially in the western Drakensberg region and, as the water cascades eastwards down the Catchment, it warms to approximately 19°C in the central regions. The present ECHAM5 climate scenario tends to under-simulate MMWTs in the centre of the Thukela Catchment and along the mainstem of the Thukela River. These results follow similar trends found with the air temperature (**Section 13.2**) and accumulated streamflow analysis (**Section 13.4**). A comparison between the MMWT simulations from the three ECHAM5 climate scenarios reveals a definite increase in MMWT under conditions of projected future climates. For the intermediate future ECHAM5 scenario (**Figure 13.29** bottom left) the Quinaries in the middle of the catchment experience a mean annual mixed maximum water temperature of approximately 21°C and this value increases to 25°C for the more distant projected future climate (**Figure 13.29** bottom right).

13.7.2 Projected changes in mean annual mixed maximum water temperatures

A mean annual difference analysis in MMWTs simulated from the three ECHAM5 climate scenarios was performed. The intermediate future minus present map (**Figure 13.30** top left) shows a warming in mean annual MMWTs, especially along the major tributaries and the mainstem of the Thukela. These Quinaries are projected to experience an increase of between 2.5 and 3°C, while the remaining Quinaries experience a smaller projected increase of between 2.0 and 2.5°C. The map showing the

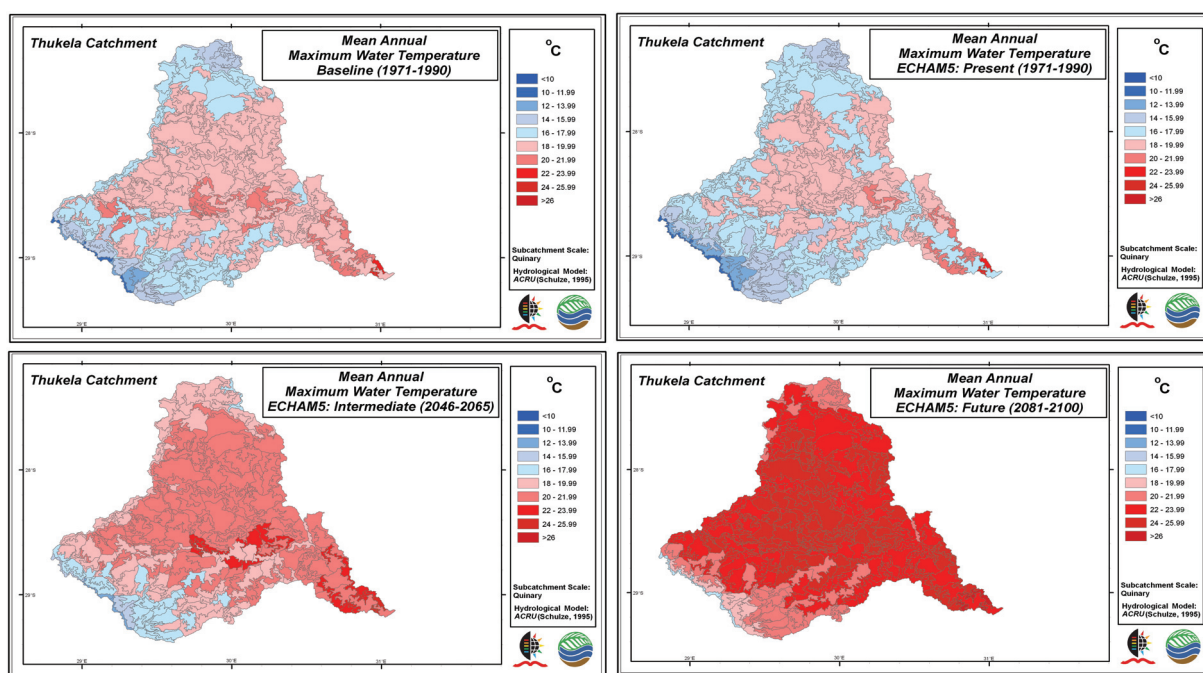


Figure 13.29 Simulated mean annual mixed maximum water temperatures generated from (top left) present baseline climate and (top right) the present ECHAM5 climate scenario, as well as (bottom left) from the intermediate future and (bottom right) more distant future ECHAM5 climate scenarios

difference between the more distant future and present ECHAM5 climates (**Figure 13.30** top right) contains the greatest increase in maximum water temperatures, with most of the Quinaries showing increases of around 5°C, but with the higher lying subcatchments tending to be more sensitive to projected climate change. **Figure 13.29** (bottom) also shows a warming trend in maximum water temperature, with a majority of the Quinaries experiencing a rise around 2.5-3°C for the distant future minus intermediate future analysis.

13.7.3 Projected changes in future means of monthly maximum mixed water temperatures for selected months

An analysis of intra-annual differences in MMWTs for selected cardinal months (**Figures 13.31-13.34**) reveals that mixed maximum water temperature changes fluctuate quite considerably throughout the year. In regard to MMWTs, January displays the highest and July the lowest values, while April and October MMWTs tend to fit between these two extremes. Mean mixed maximum water temperatures for the western Drakensberg are ~ 18°C for January and this value decreases to 13°C for April and October and falls to 10°C for July. This natural fluctuation is important in terms of aquatic organism as these changes act as cues for the initiation of certain lifecycle stages.

A comparison of MMWTs derived from the baseline present climate (top left in **Figures 13.31-13.34**) and the ECHAM5 present climate (top right in **Figures 13.31-13.34**) for the four cardinal months, indicates that this GCM is performing well in certain months and less so in others. The January analysis shows that the GCM is under-simulating MMWTs, particularly in the southwestern regions of the Thukela Catchment. April and July both show close correlations between the baseline and the simulated ECHAM5 present climates. On the other hand, October MMWTs do not show a close relationship to those from the GCM simulated climate, with under-simulations of mixed maximum

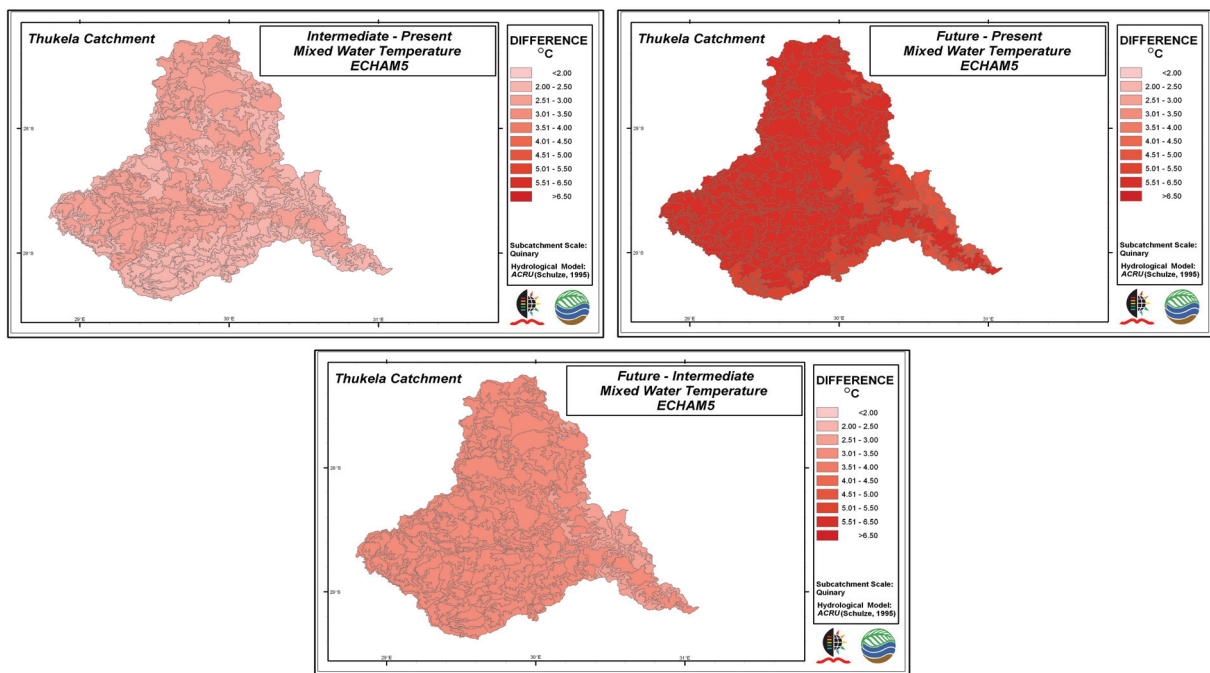


Figure 13.30 Ratios of mean annual mixed maximum water temperatures derived from (top left) intermediate future to present, (top right) more distant future to present, and (bottom) distant to intermediate future ECHAM5 climate scenarios

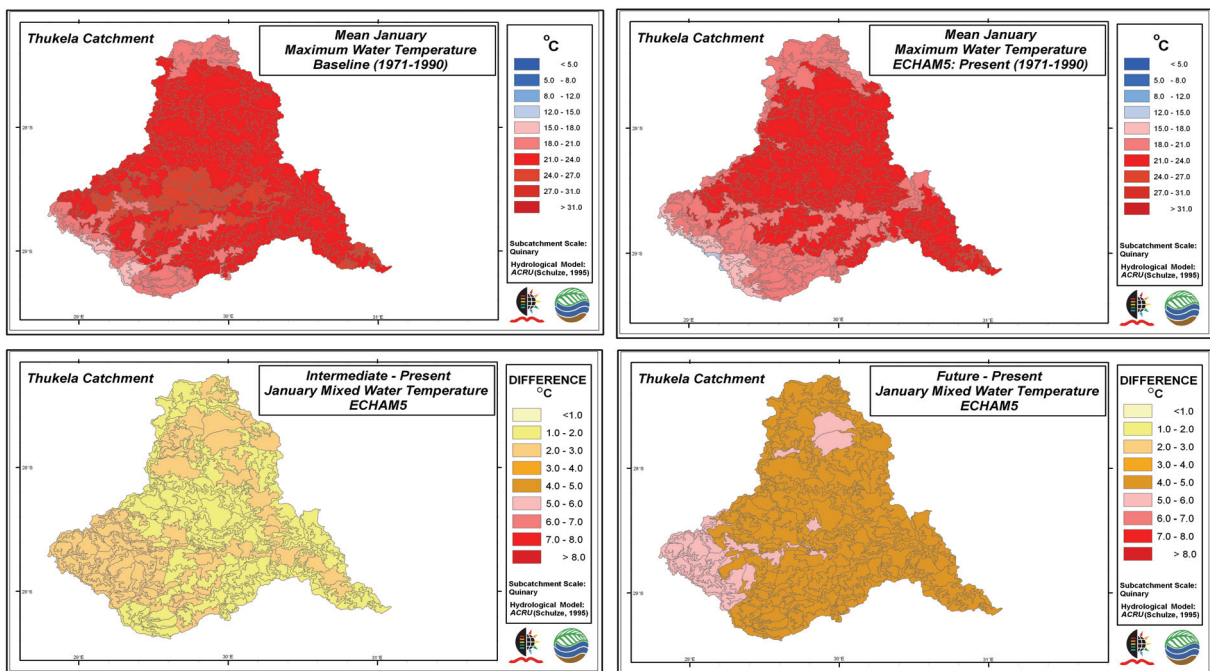


Figure 13.31 Mean January mixed maximum water temperatures in the Thukela Catchment simulated from (top left) present baseline climate vs (top right) the present ECHAM5 climate scenario, and (bottom left) differences between projected January intermediate future and present, and (bottom right) more distant future and present mixed maximum water temperatures

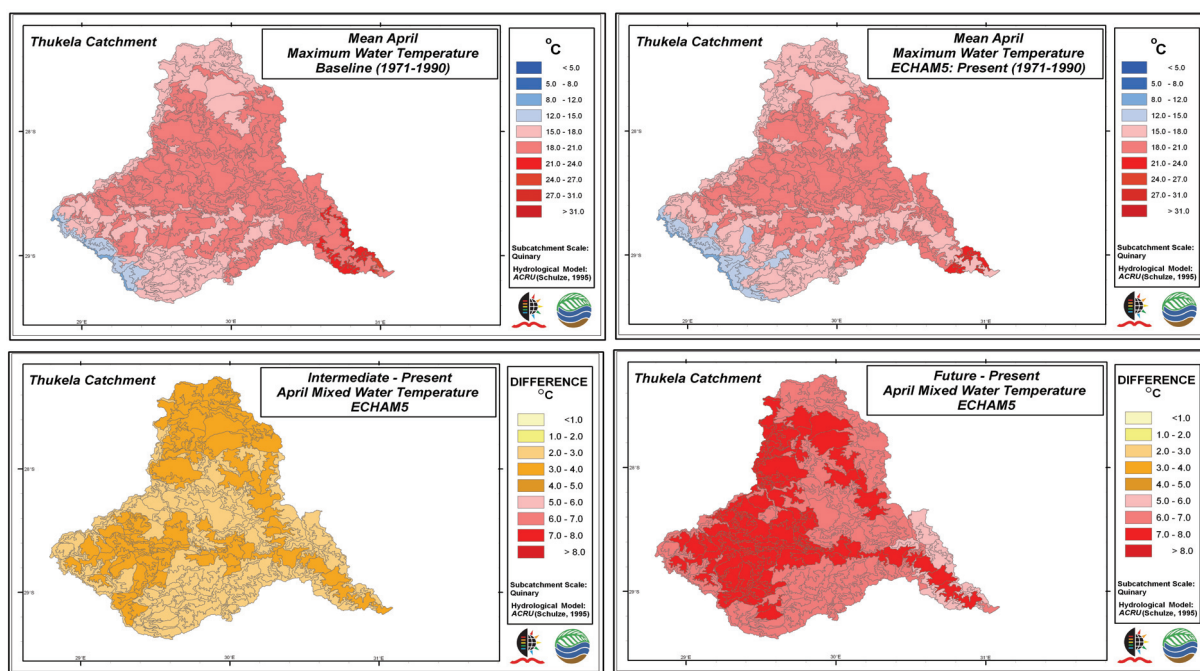


Figure 13.32 Mean April mixed maximum water temperatures in the Thukela Catchment simulated from (top left) present baseline climate vs (top right) the present ECHAM5 climate scenario, and differences between projected April intermediate future and present (bottom left), and distant future and present (bottom right) mixed maximum water temperatures

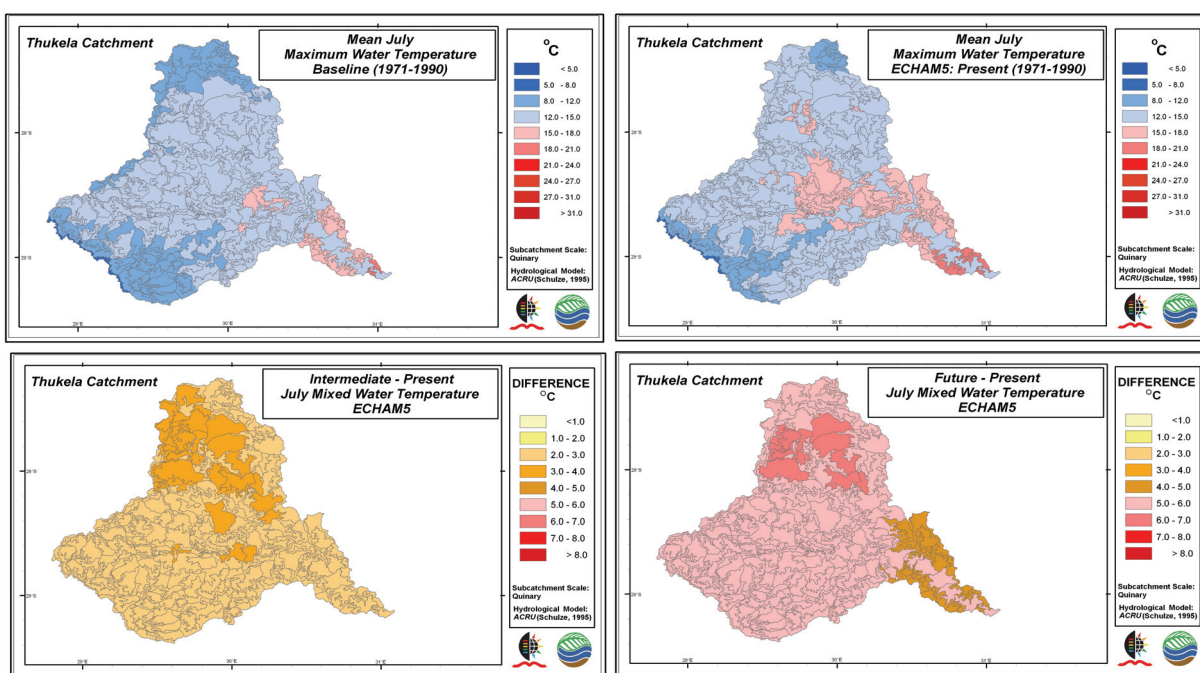


Figure 13.33 Mean July mixed maximum water temperatures in the Thukela Catchment simulated from (top left) present baseline climate vs (top right) the present ECHAM5 climate scenario, and differences between projected July intermediate future and present (bottom left), and more distant future and present (bottom right) mixed maximum water temperatures

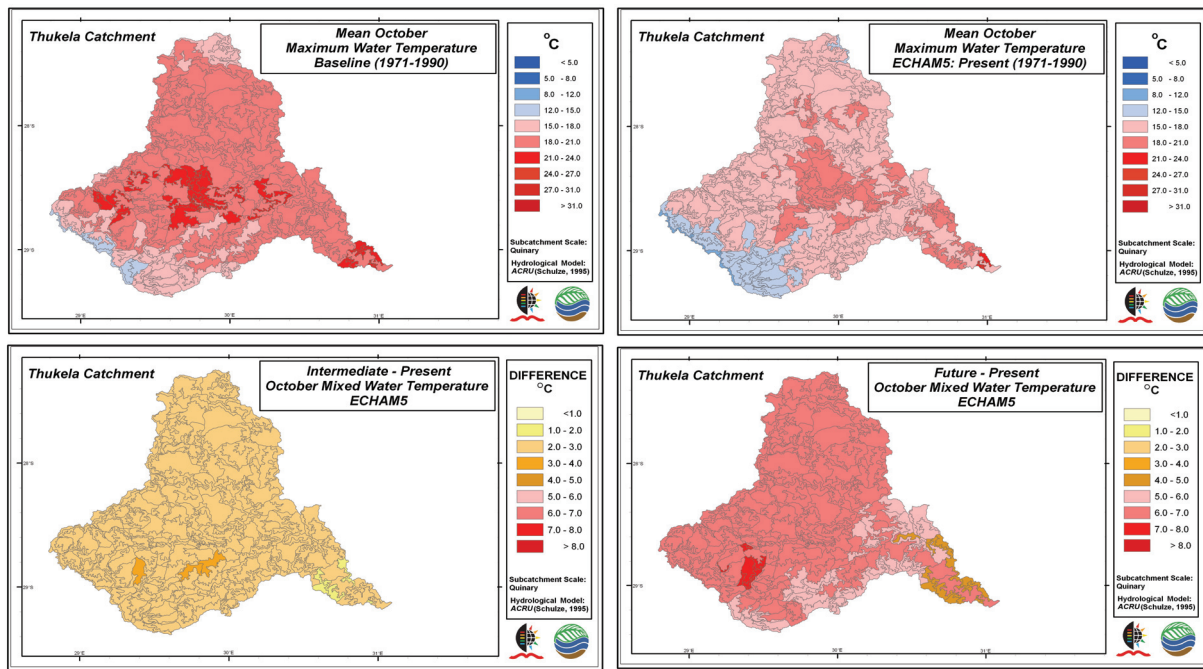


Figure 13.34 Mean October mixed maximum water temperatures in the Thukela Catchment simulated from (top left) present baseline climate vs (top right) the present ECHAM5 climate scenario, and differences between projected October intermediate future and present, and (bottom left) distant future and present (bottom right) mixed maximum water temperatures

water temperatures by over 3°C in the central parts of the Thukela. This probably stems from a noticeable under-simulation of accumulated streamflows for the present ECHAM5 scenario (**Section 13.4**).

A difference analysis in MMWTs generated from the three ECHAM5 scenarios was also performed for the four cardinal months. All months project an increase in MMWTs over time, with the difference between the distant future and present climate scenarios experiencing the greatest increase. January shows the least change in MMWTs, but still demonstrates noticeable downstream warming along the major tributaries and the mainstem of the Thukela. The intermediate future minus present MMWTs (**Figure 13.31** bottom left) project increases of between 2 and 3°C down these main stems and this difference increases to between 4 and 5°C down these main river valleys for the distant future minus present analysis (**Figure 13.31** bottom right). April also shows noticeable warming down the primary tributaries of approximately 3.5°C between the intermediate future and present climate scenarios, and this value increases to over 7°C for the distant future minus present climate scenarios of the ECHAM5 GCM (**Figure 13.32**). This trend of warmer mainstems and cooler adjacent Quinaryes is important and could imply that these adjacent Quinaryes could be used as refugia for species that prefer cooler waters. July and October (**Figures 13.33** and **13.34**) both show similar trends to one another in terms of a projected increase in mixed maximum water temperature for the intermediate future minus present scenarios, with differences of between 2 and 3°C in the central parts of the Catchment.

In **Chapter 13** an assessment was made of the potential impacts of climate change on the water temperature related indicators using the baseline climate conditions and the ECHAM5 climate scenarios. This spatial assessment was performed for the 258 hydrologically interlinked and cascading Quinary Catchments, which constitute the Thukela Catchment. In this Chapter a series of maps was used to spatially analyse air temperature, individual catchment runoff, accumulated

streamflows, mixed maximum water temperature and two water temperature indices. In **Chapter 14**, which follows, a time series analysis is employed in order to assess the potential temporal impacts of climate change on water temperature related indicators in the Thukela Catchment.

13.8 References

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CHAPTER 14 RESULTS 4: TIME SERIES ANALYSES OF WATER TEMPERATURES WITH CLIMATE CHANGE IN THE THUKELA CATCHMENT USING THE ECHAM5/MPI-OM GENERAL CIRCULATION MODEL

K.R. Barichievy and R.E. Schulze

14.1 Setting the Scene

In the Engineering Statistics Handbook (2006) a time series is defined as an ordered sequence of values of a variable at uniformly spaced time intervals. For a number of years researchers have applied time series analyses in order to interpret the temporal characteristics and trends of hydrological processes (Duffy and Gelhar, 1985). According to the Australian Bureau of Statistics (2008), three components constitute a time series, *viz.*

- the *trend* (long term direction),
- the *seasonal* (i.e. systematic) *variation* based on calendar related movements and
- the *irregular* (i.e. unsystematic) *variation* and short term fluctuations.

The purpose of the time series analyses described in this chapter is to observe and describe these three components based on the water temperature indicators identified in **Chapter 13** for climate change conditions in 15 selected Quinary Catchments located in the Thukela Catchment. Spatial and temporal analyses were performed on the following indicators:

- Mean Air Temperature,
- Individual Subcatchment Runoff,
- Accumulated Streamflows, and
- Mixed Maximum Water Temperature.

The time series analyses were performed on the three ECHAM5/MPI-OM GCM scenarios (cf. **Chapter 9** for full description), *viz.*

- Present Climate from the ECHAM5/MPI-OM GCM (1971-1990), an
- Intermediate Future Climate (2046-2065), and a more
- Distant Future Climate (2081-2100).

Results from the present baseline climate scenario are not compared against those of the present ECHAM5/MPI-OM (hereafter referred to in its abbreviated form of ECHAM5) climate scenario as they are not temporally conditioned and hence do not have a temporal correlation. The time series used is at an annual time step for each of the aforementioned indicators for the entire respective 20 years of record.

The time series analyses use two methods to describe how each water temperature related indicator may vary over time, *viz.*

- How does an indicator vary for a single Quinary catchment by comparing the three ECHAM5 climate scenarios (i.e. a temporal analysis), with the hypothesis being that in future climates temperatures are increasing and streamflows are changing; and
- How does an indicator vary between the three Quinaries making up a Quaternary Catchment for a single climate scenario (i.e. a spatial analysis), with the hypothesis being that Quinaries within a

Quaternary are altitude determined and therefore have influences on temperature, rainfall, hence on runoff and thus also on water temperature patterns.

14.2 Catchment Selection

In total 15 Quinary Catchments, which make up five Quaternaries, were selected in the Thukela to undergo time series analyses. The location of these 15 Quinaries is shown in **Figure 14.1**. From **Figure 14.1**, and with reference also to **Figures 5.2** (altitude), **5.4** (ecological regions) and **5.8** (mean annual streamflows) it may be seen that the selected catchments are in different hydroclimatic regions within the Thukela Catchment in order to determine how different areas might respond to projected climate change. **Table 14.1** summarises the characteristics of the 15 selected subcatchments.

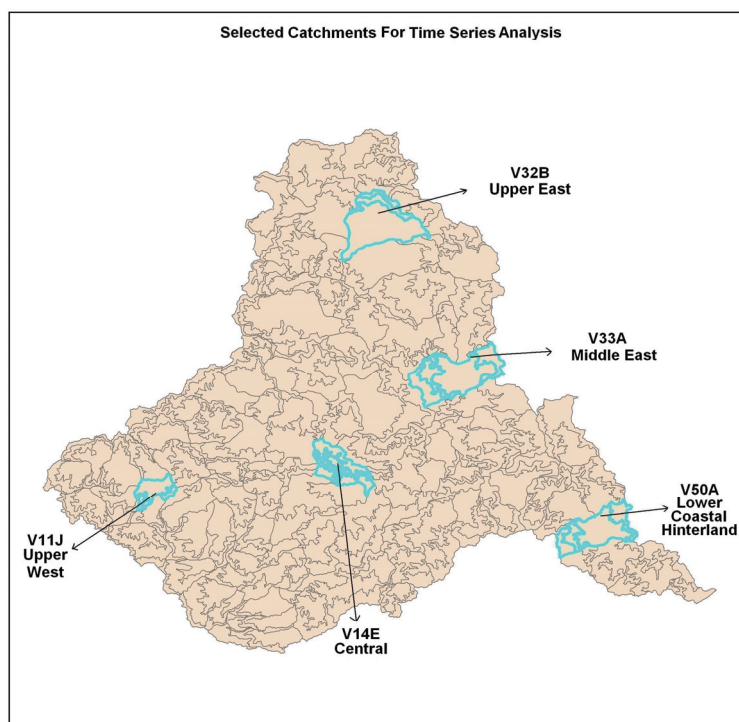


Figure 14.1 Locations of the selected Quinary Catchments for time series analyses

Table 14.1 Characteristics of the 15 selected Quinary Catchments

Quaternary Catchment Number	BEEH Quinary Catchment Number	Mean Catchment Altitude (m)	Relative Location of Catchment	Catchment Area (km ²)	River System
V11J	4846	1465	Upper West	14.50	Upper Thukela
	4847	1266		33.34	
	4848	1175		95.93	
V14E	4906	1021	Central	143.54	Upper Thukela
	4907	897		76.68	
	4908	780		68.48	
V32B	5020	1835	Upper North	34.00	Buffalo
	5021	1472		70.52	
	5022	1245		456.28	
V33A	5041	1460	Middle East	105.77	Buffalo
	5042	1295		188.09	
	5043	1140		290.31	
V50A	5068	975	Lower Coastal Hinterland	53.85	Lower Thukela
	5069	535		78.02	
	5070	286		57.31	

14.3 Time Series Analyses of Air Temperature

14.3.1 Projected changes in air temperature in a single Quinary Catchment with climate change

The values produced by the time series analysis all indicate that air temperature is likely to increase under the projected conditions of climate change for all the selected Quinaries. This is illustrated in **Figures 14.2-14.4** by way of time series plots from selected Quinaries. **Figure 14.2** shows a time series of annual means of air temperature for Quinary 4848, located in the high altitude upper western part of the Thukela Catchment. Annual means of air temperature are shown to remain relatively constant over the 20 years of a climate scenario, but there are significant differences between the three ECHAM5 scenarios. The air temperature for the present ECHAM5 climate scenario for Quinary 4848 (**Figure 14.2**) is approximately 17°C, with this value increasing to approximately 20°C for the intermediate future ECHAM5 climate and finally to around 23°C for the more distant future ECHAM5 climate. Essentially air temperature is thus projected to increase significantly over time, with the present ECHAM5 climate displaying the lowest temperatures, the future ECHAM5 climate being the highest and the intermediate ECHAM5 being somewhere between these two extremes. This increasing trend between annual means of air temperatures in the ECHAM5 scenarios was found in all 15 selected Quinaries evaluated.

By comparing **Figures 14.2-14.4** one can determine how spatial location can influence the temporal characteristics of air temperature. **Figure 14.2** represents Quinary 4848 located in the upper Thukela, **Figure 14.3** represents Quinary 4908 located in the central parts of the Thukela Catchment and **Figure 14.4** represents Quinary 5070 located in the lower altitude Coastal Hinterland. By comparing the annually averaged air temperatures of each ECHAM5 climate scenario it can be concluded that air temperatures increase as one moves from higher altitudes towards the lower altitude warmer coastal zones, in accordance with lapse rate decreases in air temperature with altitude (Schulze and Maharaj, 2004) and the moderating influence of the warm Indian Ocean. For all three ECHAM5 scenarios Quinary 4848, located in the upper west Thukela, is approximately 2°C cooler than Quinary 4908, located in the centre of the Thukela Catchment and is around 3°C cooler than Quinary 5070, which is located near the coast.

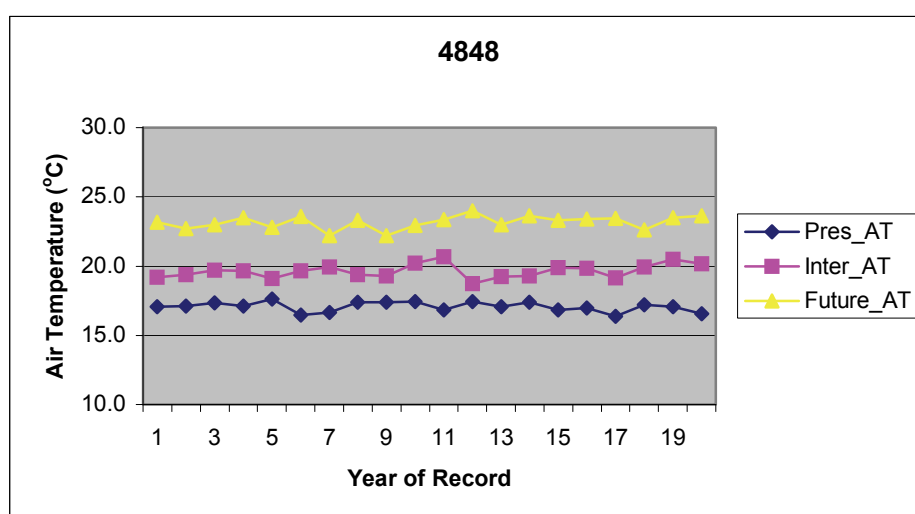


Figure 14.2 A time series of annual means of air temperature (°C) for Quinary 4848 of Quaternary Catchment V11J for present, intermediate future and distant future ECHAM5 climate scenarios

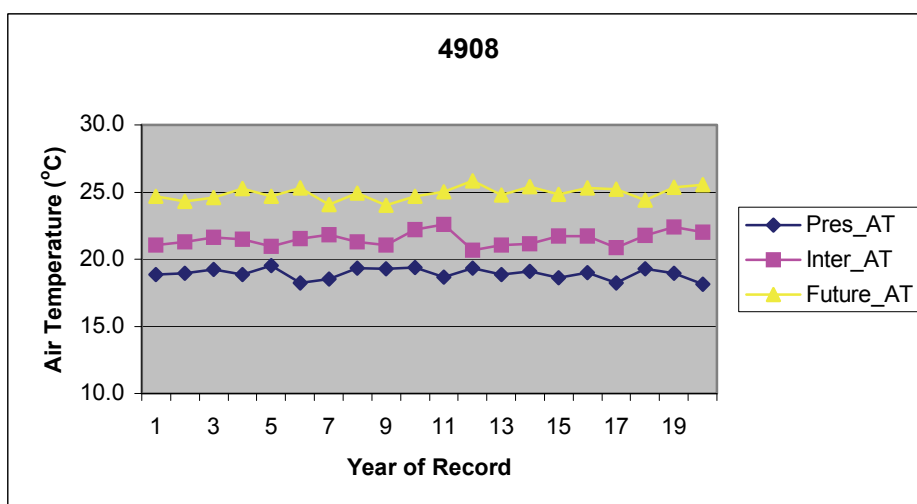


Figure 14.3 A time series of annual means of air temperature (°C) for Quinary 4908 of Quaternary Catchment V14E for present, intermediate future and distant future ECHAM5 climate scenarios

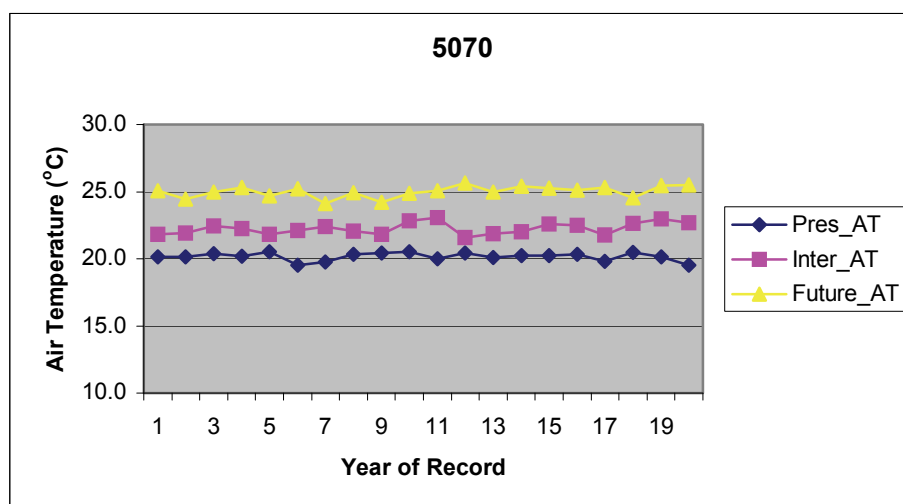


Figure 14.4 A time series of annual means of air temperature (°C) for Quinary 5070 of Quaternary Catchment V50A for present, intermediate future and distant future ECHAM5 climate scenarios

Closer scrutiny of the times series indicates a rising air temperature trend *within* the 20 years of values in both the projected intermediate and distant future climates - a trend which is not visible in the present climate scenario. This increasing trend can be clearly observed when a linear trend line is placed over the individual times series (**Figures 14.5-14.7**). This is an important result as it indicates that air temperature is likely to increase steadily even over a relatively short 20 year period of time.

14.3.2 Variations in air temperature between the Quinaries making up a Quaternary Catchment for a single climate scenario

The second method describing how air temperatures may vary over time explores how it fluctuates between the three altitudinally defined Quinaries (Upper, Middle and Lower; cf. **Chapter 6**) of a Quaternary Catchment, for a single ECHAM5 climate scenario. **Figure 14.8** displays a typical time series using this method of analysis and all 15 selected catchments follow the same overall trend.

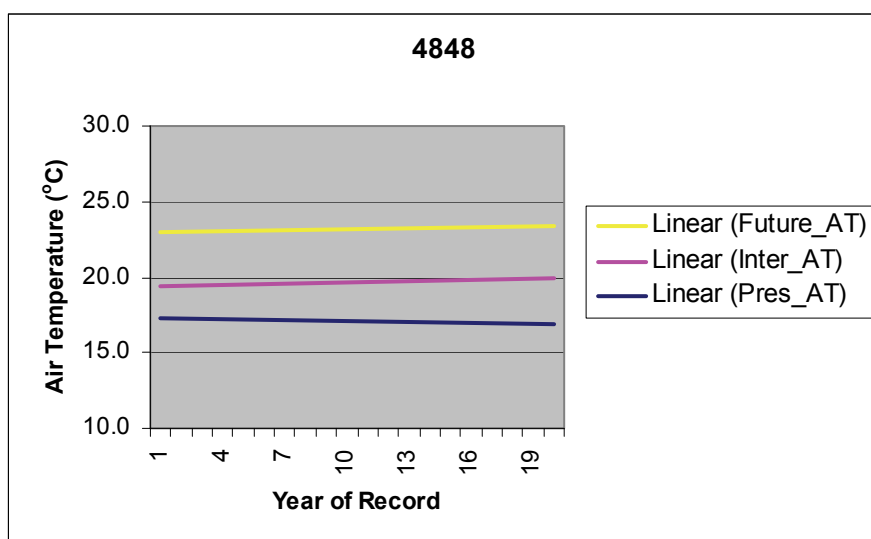


Figure 14.5 Linear trends of annual means of air temperature (°C) for Quinary 4848 of Quaternary Catchment V11J for present, intermediate future and distant future ECHAM5 climate scenarios

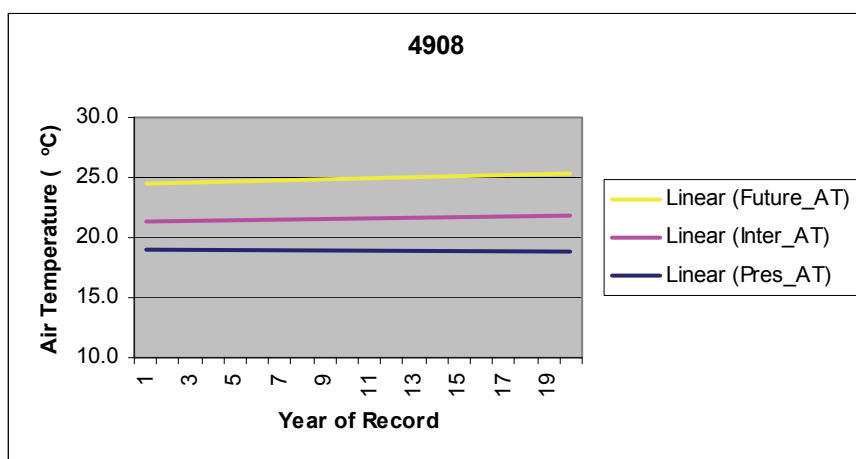


Figure 14.6 Linear trends of annual means of air temperature (°C) for Quinary 4908 of Quaternary Catchment V14E for present, intermediate future and distant future ECHAM5 climate scenarios

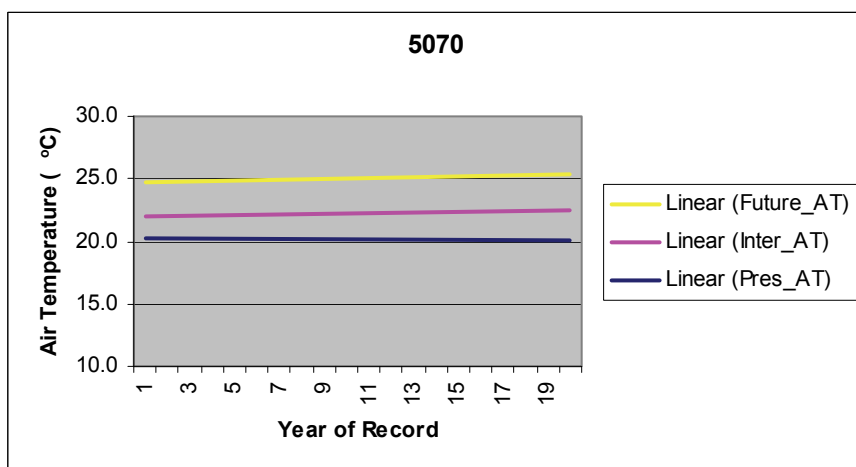


Figure 14.7 Linear trends of annual means of air temperature (°C) for Quinary 5070 of Quaternary Catchment V50A for present, intermediate future and distant future ECHAM5 climate scenarios

Figure 14.8 shows that the higher lying Upper Quinary catchment (5020; altitude 1835 m) of Quaternary V32B has the lowest annual means of air temperature compared to those of the Middle (5021; altitude 1472 m) and Lower Quinaries (5022; altitude 1245 m), with the latter experiencing the highest air temperatures. By comparing the differences in air temperature between each Quinary one is able to infer the significance of the altitude differences between the three Quinaries within a single Quaternary and the value of simulating at Quinary Catchment scale.

Visual comparison of results in **Figures 14.8-14.10** indicates an increased variability in annual means of air temperature from one climate scenario to the next into the future. For example, the annual means of air temperature for the present ECHAM5 climate scenario (**Figure 14.8**) appear reasonably stable, with a few spikes over the 20 year record, compared with those of the intermediate and distant future ECHAM5 climate scenarios (**Figures 14.9 and 14.10**), which project a higher variation in air temperature from one year to the next over their 20 years of record. An increase in the variability of future air temperature, important to water temperatures, can be quantified by calculating the standard deviations of the annual means of air temperature for the three ECHAM5 climate scenarios (**Table 14.2**). Standard deviation is a measure of dispersal around the mean and is a commonly used measure of variability of a temperature time series (e.g. Schulze, 2007). The results from this test support the visual conclusions from the graphical analysis that air temperature variability is, indeed, increasing in the intermediate and distant futures. From **Table 14.2** it is seen that standard deviations for the intermediate and future ECHAM5 climate scenarios are increasing by an average of 38 and 30% respectively, compared to those of the present ECHAM5 scenario. Furthermore, there does not seem to be a regional trend in the magnitudes of standard deviations. Ultimately, therefore, annual air temperature is projected to fluctuate more in the intermediate and distant futures than at present, which could very well have serious implications for aquatic ecosystems and the species that inhabit them.

14.3.3 Conclusions on time series analyses of air temperature

In conclusion, both methods used to describe how air temperature varies over time indicate that annual means of air temperature and their variability, derived from the ECHAM5 GCM, are likely to

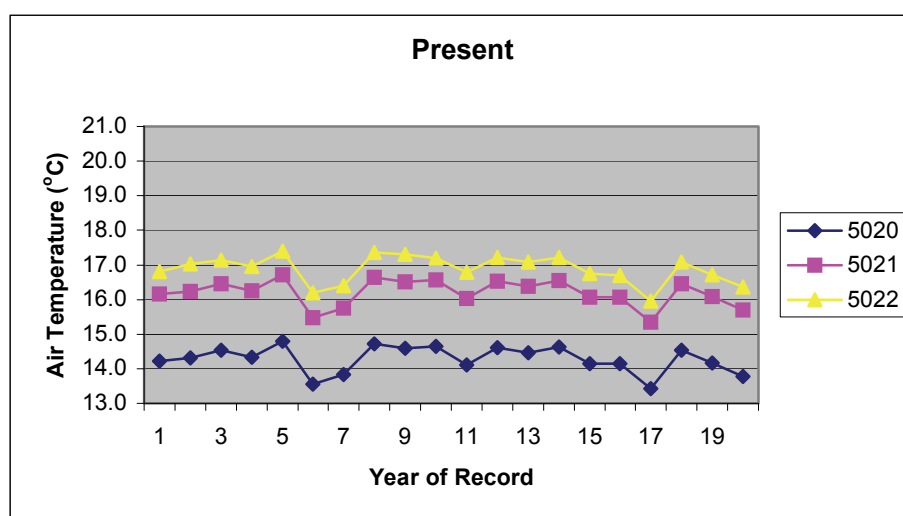


Figure 14.8 A time series of annual means of air temperature (°C) for Quinaries 5020, 5021 and 5022 of Quaternary Catchment V32B for the present ECHAM5 climate scenario

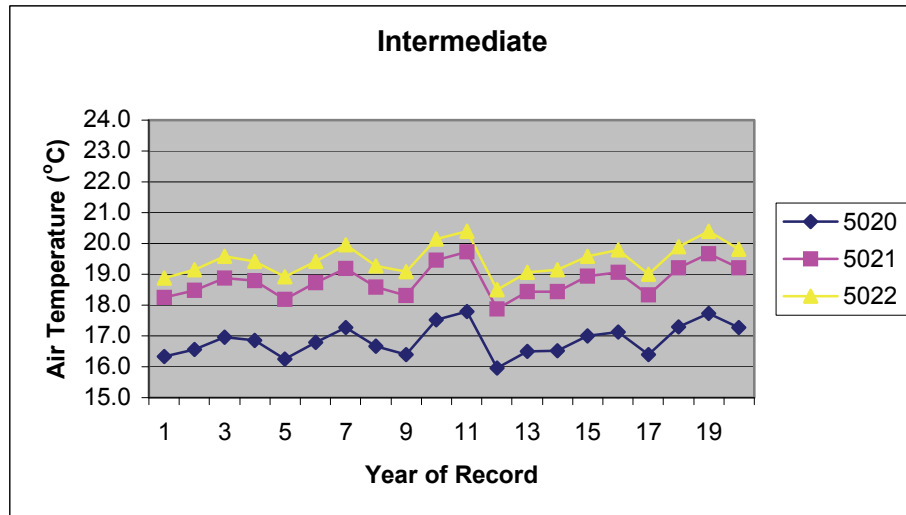


Figure 14.9 A time series of annual means of air temperature (°C) for Quinaries 5020, 5021 and 5022 of Quaternary Catchment V32B for the intermediate future ECHAM5 climate scenario

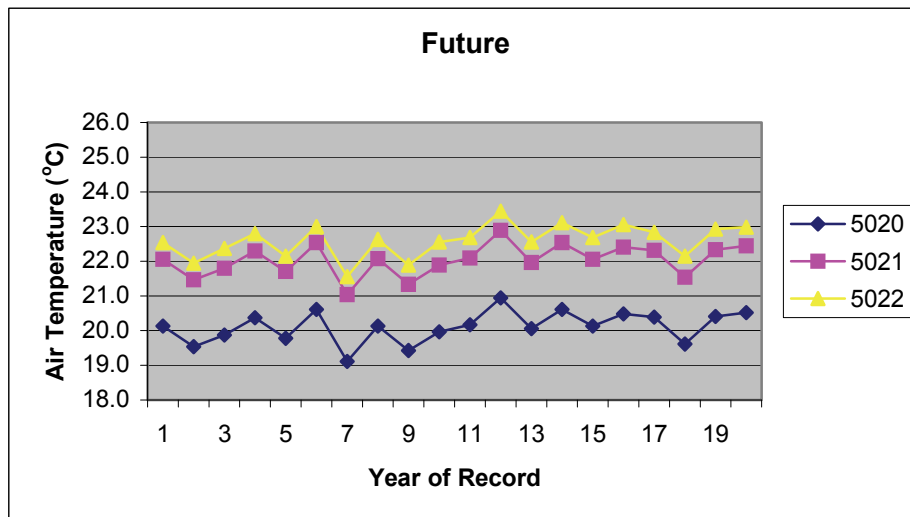


Figure 14.10 A time series of annual means of air temperature (°C) for Quinaries 5020, 5021 and 5022 of Quaternary Catchment V32B for the distant future ECHAM5 climate scenario

increase in the intermediate (2046-2065) and more distant (2081-2100) futures. Furthermore, there is a noticeable difference in air temperatures between the three Quinaries within a single Quaternary Catchment as a result of altitudinal differences. For both cases the hypotheses set out in **Section 14.1** have been confirmed.

14.4 Time Series Analyses of Runoff from Individual Subcatchments

14.4.1 Projected changes in runoff from a single Quinary Catchment with climate change

The result from the time series analysis for annual runoff from individual subcatchments does not show a distinct pattern of change in runoff over the three ECHAM5 scenarios (**Figures 14.11-14.13**).

Table 14.2 A summary of standard deviations of annual means of air temperature for the 15 selected Quinary Catchments for 20 years of present (P), intermediate future (I) and distant future (F) ECHAM5 climate scenarios

Quinary Number	Standard Deviation (°C) Present	Standard Deviation (°C) Intermediate	Standard Deviation (°C) Future	I: P	F: P	F: I
4846	0.35	0.49	0.48	1.42	1.39	0.98
4847	0.36	0.50	0.47	1.41	1.31	0.93
4848	0.35	0.50	0.47	1.42	1.33	0.94
4906	0.41	0.51	0.51	1.25	1.24	0.99
4907	0.41	0.52	0.51	1.26	1.24	0.99
4908	0.41	0.52	0.50	1.29	1.22	0.95
5020	0.39	0.51	0.46	1.31	1.18	0.89
5021	0.39	0.51	0.46	1.32	1.18	0.90
5022	0.40	0.53	0.47	1.30	1.17	0.90
5041	0.37	0.53	0.47	1.43	1.26	0.88
5042	0.35	0.52	0.46	1.46	1.30	0.90
5043	0.37	0.53	0.47	1.43	1.26	0.88
5068	0.32	0.49	0.48	1.53	1.52	0.99
5069	0.31	0.45	0.42	1.45	1.37	0.94
5070	0.30	0.44	0.42	1.47	1.39	0.94

Figures 14.11-14.13 show time series plots for three Quinaries from different regions of the Thukela Catchment and they share the same y-axis scale for ease of comparison. All the aforementioned figures indicate a similar overall trend in that annual runoff, in the intermediate and distant futures, could experience more inter-annual variations with larger spikes in annual runoff volumes being evident. For example, closer scrutiny of results from Quinary 5042 (**Figure 14.13**), which is located in the middle to east of the Thukela Catchment, shows that the distant future climate scenario typically displays larger annual runoff volumes than those from the intermediate future and present ECHAM5 scenarios, indicating that larger runoff events are projected to occur under future climatic conditions.

The issue of how the runoff variability from individual subcatchments is likely to change in the future was deemed important for a water temperature study and was therefore quantified by calculating both the standard deviations and the coefficients of variation of annual runoff for all 15 selected Quinaries for the three ECHAM5 climate scenarios. Standard deviation is an absolute measure of dispersal around the mean while the coefficient of variation is a normalised, i.e. relative, measure of dispersion and is defined as the ratio of the standard deviation to the mean, expressed as a percentage (**Equation 14.1**), i.e.

$$\text{Coefficient of Variation (C}_v\text{)} = \frac{(\text{Standard Deviation})}{(\text{Mean})} * 100 \quad [14.1]$$

In **Table 14.3** the results of standard deviations from the 15 selected catchments for individual subcatchment annual runoff are presented. These indicate that standard deviations for individual subcatchment runoff are likely to increase in the intermediate and more distant futures. From **Table 14.3** standard deviations of runoff derived from the intermediate and future ECHAM5 climate scenarios are increasing by an average factor of 1.74 and 2.10 respectively, compared to those of the present ECHAM5 scenario. This is a significant increase in inter-annual variability, particularly for the distant future scenario, where a doubling in standard deviations for annual runoff from individual subcatchments is projected.

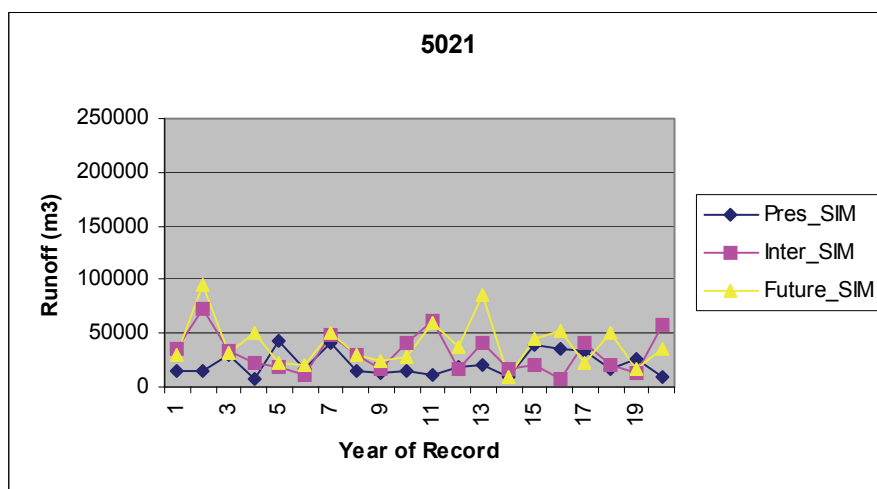


Figure 14.11 A time series of individual subcatchment annual runoff (m^3) for Quinary 5021 in Quaternary Catchment V32B for present, intermediate future and distant future ECHAM5 climate scenarios

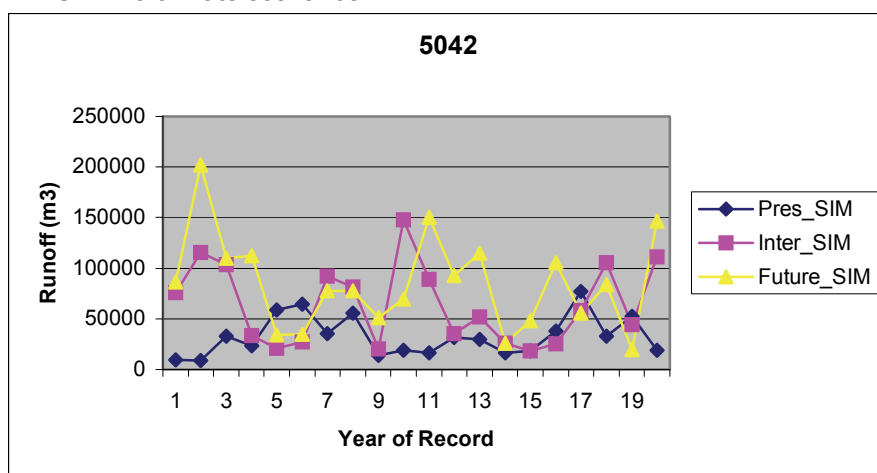


Figure 14.12 A time series of individual subcatchment annual runoff (m^3) for Quinary 5042 in Quaternary Catchment V33A for present, intermediate future and distant future ECHAM5 climate scenarios

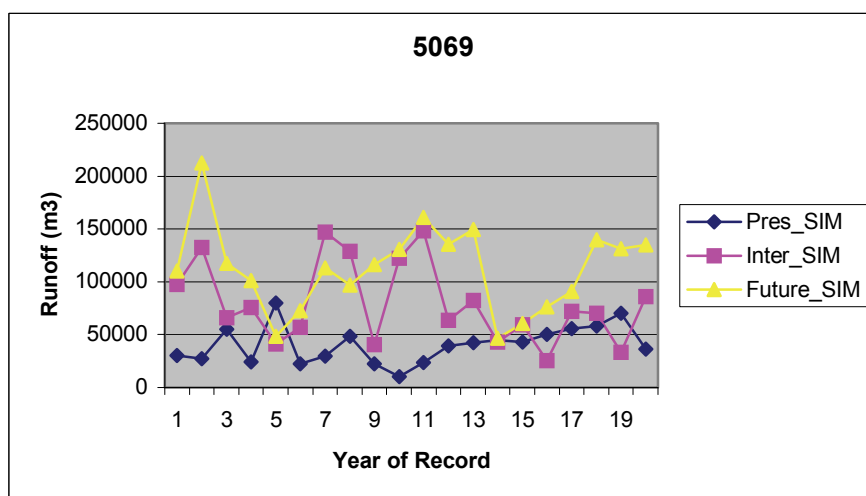


Figure 14.13 A time series of individual subcatchment annual runoff (m^3) for Quinary 5069 in Quaternary Catchment V50A for present, intermediate future and distant future ECHAM5 climate scenarios

Table 14.3 A summary of standard deviations (m^3) of individual subcatchment annual runoff derived from the 15 selected Quinary Catchments derived from present (P), intermediate future (I) and distant future (F) ECHAM5 climate scenarios

Quinary Number	Standard Deviation (m^3) Present	Standard Deviation (m^3) Intermediate	Standard Deviation (m^3) Future	I: P	F: P	F: I
4846	5065	5562	6865	1.10	1.36	1.23
4847	8158	8957	12152	1.10	1.49	1.36
4848	19118	1274	29426	1.11	1.54	1.38
4906	22993	34258	43446	1.49	1.89	1.27
4907	10915	16390	21553	1.50	1.97	1.32
4908	8471	13404	18329	1.58	2.16	1.37
5020	5840	9624	11384	1.65	1.95	1.18
5021	11375	18214	21935	1.60	1.93	1.20
5022	43993	71542	96027	1.63	2.18	1.34
5041	8960	20878	25035	2.33	2.79	1.20
5042	19566	39363	46531	2.01	2.38	1.18
5043	27736	59047	72229	2.13	2.60	1.22
5068	5659	13931	14862	2.46	2.63	1.07
5069	17664	38096	40433	2.16	2.29	1.06
5070	19650	44401	46912	2.26	2.39	1.06

In **Table 14.4**, on the other hand, the results of inter-annual coefficients of variation (C_v) of runoff for the 15 selected catchments are summarised. These show an entirely different set of results to those of standard deviations. The C_v s from the intermediate ECHAM5 climate scenario remain relatively constant (a ratio close to unity) compared to those from the present ECHAM5 scenario. The ratio comparison actually shows a slight decrease in C_v for the distant future to present and distant to intermediate future ECHAM5 climate scenarios. It may thus be concluded that the standard deviation

Table 14.4 A summary of inter-annual coefficients of variation (%) of individual catchment runoff derived from the 15 selected Quinary Catchments derived from present (P), intermediate future (I) and distant future (F) ECHAM5 climate scenarios

Quinary Number	Coefficient of Variation (%) Present	Coefficient of Variation (%) Intermediate	Coefficient of Variation (%) Future	I: P	F: P	F: I
4846	43.83	31.27	28.42	0.71	0.65	0.91
4847	50.42	35.14	34.63	0.70	0.69	0.99
4848	55.86	38.52	38.14	0.69	0.68	0.99
4906	45.49	45.51	41.16	1.00	0.90	0.90
4907	48.62	48.18	44.20	0.99	0.91	0.92
4908	50.15	51.35	46.61	1.02	0.93	0.91
5020	49.22	56.26	52.37	1.14	1.06	0.93
5021	52.58	57.88	55.12	1.10	1.05	0.95
5022	70.29	73.20	73.62	1.04	1.05	1.01
5041	48.31	58.36	53.42	1.21	1.11	0.92
5042	60.00	61.35	54.77	1.02	0.91	0.89
5043	58.18	63.08	56.99	1.08	0.98	0.90
5068	42.32	50.05	37.62	1.18	0.89	0.75
5069	43.44	47.88	35.98	1.10	0.83	0.75
5070	52.30	56.64	41.76	1.08	0.80	0.74

of individual subcatchment runoff is increasing markedly while its C_v is remaining relatively constant or actually decreasing in the intermediate and more distant futures, implying that the means are increasing at a similar rate to the absolute variability. The standard deviation ratio analysis for individual subcatchment runoff also displays a regional trend, indicating an increase in values over time as one moves from the upper (higher altitude) to the lower altitude regions of the Thukela Catchment.

A comparison of Quinaries 5021, 5042 and 5069 (**Figures 14.11-14.13**) allows one to determine what effects catchment area and location within the Thukela have on individual subcatchment runoff. Quinary 5021 is located in the upper north of the Thukela Catchment and has a catchment area of 70.5 km². Quinary 5069 has a similar catchment area of 78.0 km², but is located in the coastal hinterland region and this difference in location has a large influence on individual subcatchment runoff volume. The coastal Quinary (5069) experiences far more runoff for all three ECHAM5 climate scenarios than that from the drier Quinary 5021. Quinary 5042 is located mid east region of the Thukela. It also generally has lower rainfall than the coastal hinterland, but shows similar runoff volumes to the coastal catchment (Quinary 5069). This similarity in runoff volume may be attributed to Quinary 5042 being more than double the catchment size at 188.7 km², thus giving this drier catchment a similar runoff volume to that of the wetter coastal Quinary. A volumetric comparison of runoff can thus be misleading and the impact of catchment area therefore needs to be taken into account in runoff comparisons.

14.4.2 Variations in individual subcatchment runoff between the Quinaries making up a Quaternary Catchment for a single climate scenario

This analysis describes how annual runoff from individual subcatchments varies over time and explores how runoff differs between the three altitudinally defined Quinaries (Upper, Middle and Lower; cf. **Chapter 6**) of a Quaternary Catchment, for a single ECHAM5 climate scenario. **Figures 14.14-14.16** show time series plots for Quaternary V14E located in the central region of the Thukela and these results are typical of the time series from this method of analysis, with all 15 selected catchments following the same overall trend. The results indicate that catchment area has a large influence on runoff volume. For example, Quinary 4906 is the largest of the three at 143 km² and thus its runoff is always greater than that from the other two smaller Quinaries, which are similar in terms of area (± 70 km²). However, due to these three Quinaries being in the same Quaternary, they all experience the same fluctuations with respect to their annual runoff. Therefore, if there is a wet year all three Quinaries will show an increase in runoff for that year. When comparing results from **Figures 14.14-14.16** it is noted that there is a definite increase in runoff volume from one scenario to the next for all Quinaries, with the distant future climate scenario (**Figure 14.16**) exhibiting the largest magnitude of flow.

14.4.3 Conclusions on time series analyses of individual subcatchment runoff

In conclusion, both methods used to describe how individual subcatchment runoff varies over time indicate that both runoff volume, derived with the *ACRU* model using output from the ECHAM5 GCM, and its absolute variability (i.e. standard deviation) are likely to increase in the intermediate (2046-2065) and more distant (2081-2100) futures, while the relative variability (i.e. C_v) is likely to remain much the same or even decrease slightly over these time periods. Furthermore, there is a noticeable difference in individual subcatchment runoff within a single Quaternary Catchment due to altitudinal and area variations. For both cases the hypotheses set out in **Section 14.1** have been confirmed.

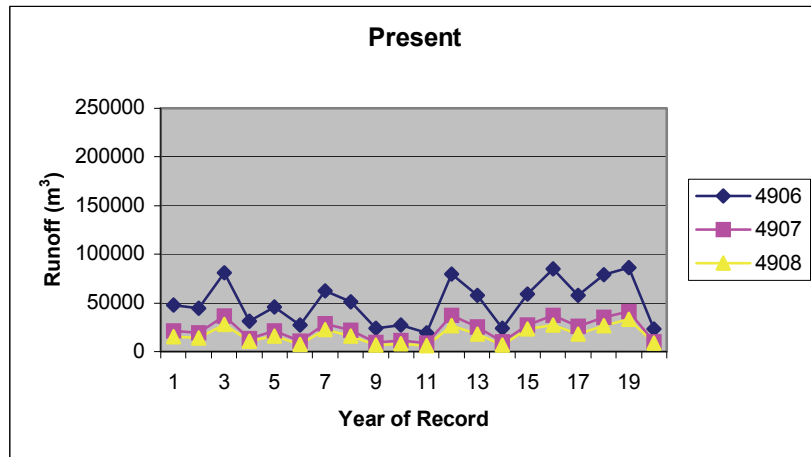


Figure 14.14 A time series of individual subcatchment annual runoff (m³) for Quinaries 4906, 4907 and 4908 within Quaternary Catchment V14E derived from the present ECHAM5 climate scenario

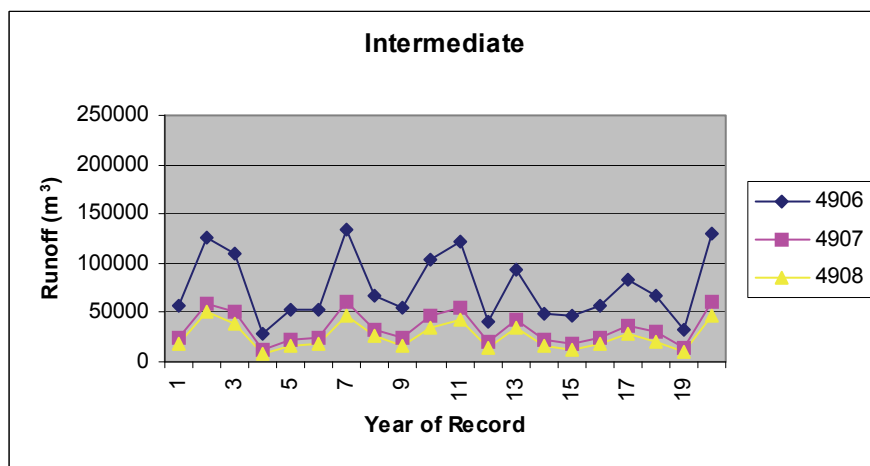


Figure 14.15 A time series of individual subcatchment annual runoff (m³) for Quinaries 4906, 4907 and 4908 within Quaternary Catchment V14E derived from the intermediate future ECHAM5 climate scenario

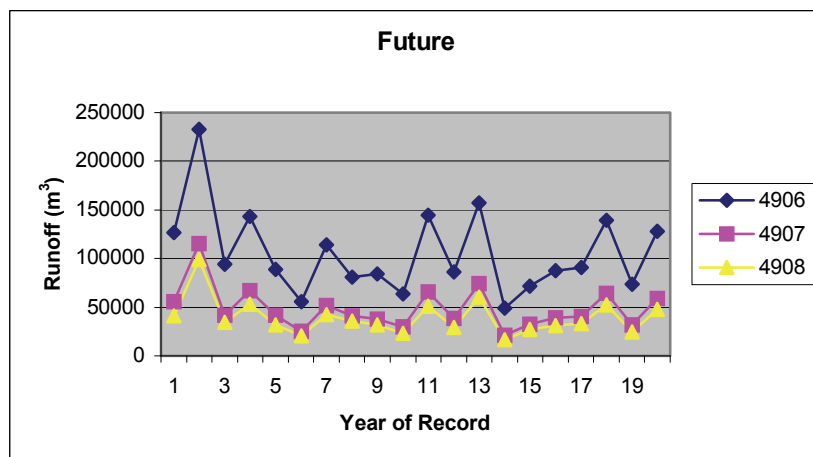


Figure 14.16 A time series of individual subcatchment annual runoff (m³) for Quinaries 4906, 4907 and 4908 within Quaternary Catchment V14E derived from the distant future ECHAM5 climate scenario

14.5 Time Series Analysis of Accumulated Catchment Streamflows

14.5.1 Projected changes in accumulated catchment streamflows from a single Quinary Catchment with climate change

Similar to the results from individual subcatchment runoff, the results produced from the time series analysis for accumulated annual streamflows do not show a distinct pattern of change over the three ECHAM5 scenarios (**Figures 14.17-14.19**). **Figures 14.17-14.19** show time series plots from three Lower Quinaries from different regions within the Thukela Catchment and it must be noted that these plots do not share the same y-axis scale owing to the large differences in streamflow magnitude between these Quinaries. Essentially Quinary 5070 in Quaternary V50A, which is located in the coastal hinterland, will have more accumulated streamflow than Quinary 4848 in Quaternary V11J which is located in the upper west of the Thukela, as more flows are routed through this lower coastal Quinary.

Figures 14.17-14.19 indicate a similar overall trend in that accumulated annual streamflows are increasing over time and the intermediate and distant future scenarios could be experiencing a higher inter-annual variation and larger spikes in annual accumulated streamflow volumes. All three aforementioned figures show that the distant future climate scenario typically generates larger accumulated streamflow volumes than the intermediate future and present ECHAM5 climate scenarios.

As in **Sections 14.3** and **14.4**, the issue of variability needs to be considered here. Variability of accumulated annual streamflows was quantified by calculating the standard deviation (**Table 14.5**) and the inter-annual coefficient of variation (**Table 14.6**) from all 15 selected Quinaries with flows derived from the three ECHAM5 climate scenarios.

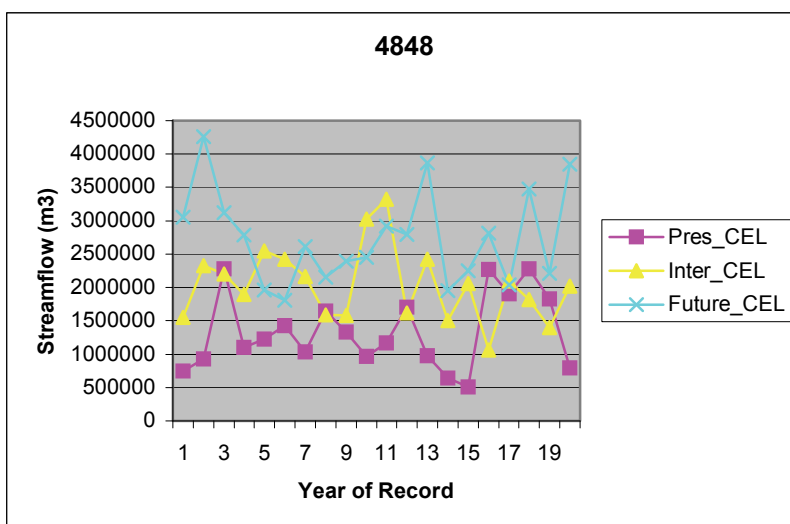


Figure 14.17 A time series of accumulated annual streamflows (m^3) for Quinary 4848 of Quaternary Catchment V11J derived from present, intermediate future and distant future ECHAM5 climate scenarios

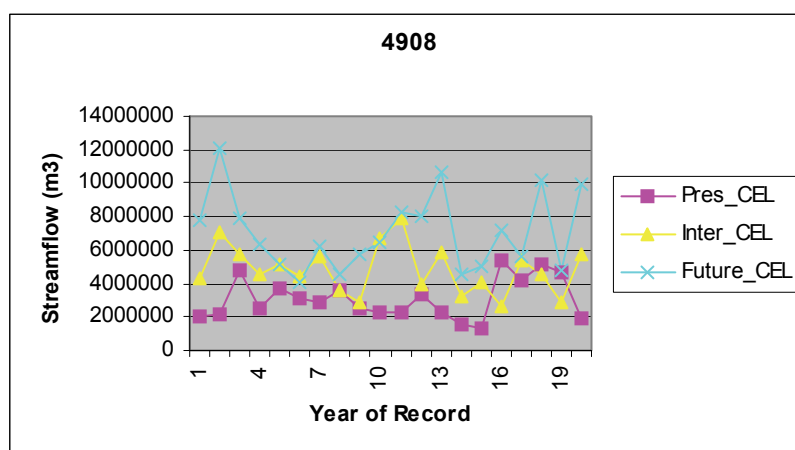


Figure 14.18 A time series of accumulated annual streamflows (m^3) for Quinary 4908 of Quaternary Catchment V14E derived from present, intermediate future and distant future ECHAM5 climate scenarios

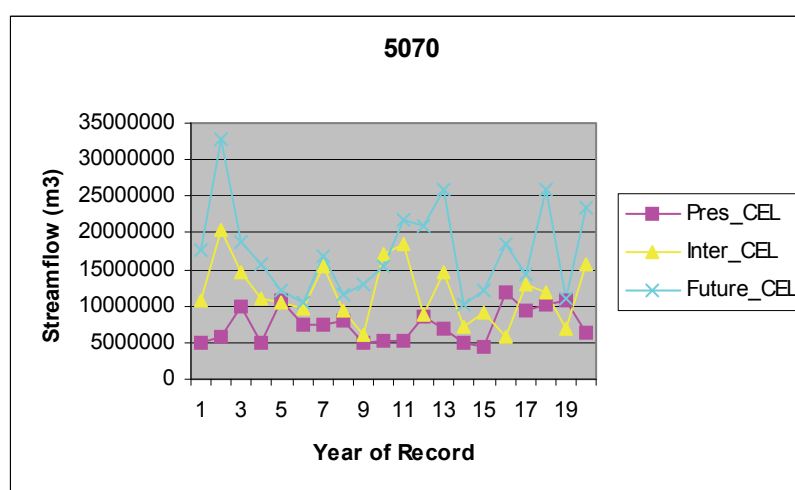


Figure 14.19 A time series of accumulated annual streamflows (m^3) for Quinary 5070 of Quaternary Catchment V50A derived from present, intermediate future and distant future ECHAM5 climate scenarios

Table 14.5 summarises the results of standard deviations for the 15 selected catchments for accumulated annual streamflows. The results indicate that standard deviations are likely to increase in the intermediate and more distant futures. The ratios of distant future to present standard deviations of accumulated flows derived from ECHAM5 climate scenarios display the greatest change, with an average increase by a factor of around 2.2. The other two ratio comparisons, between the intermediate future and present, and the more distant and intermediate futures, also point to increases in standard deviation for accumulated streamflows, but to a lesser degree. The position of the Quinary within the larger Quaternary Catchment also appears to influence standard deviations of accumulated annual streamflows, with the Lower Quinaries, the flows of which are modulated by accumulated flows from upstream, tending to have lower standard deviations than the Upper and Middle Quinaries.

Table 14.6 summarises the results of the inter-annual coefficients of variation (C_v) for the 15 selected subcatchments for accumulated streamflows. The table shows an entirely different set of results to those of the standard deviations, with the C_v s for the intermediate ECHAM5 climate scenario

Table 14.5 A summary of standard deviations (m^3) of accumulated annual streamflows for the 15 selected Quinary Catchments derived from present, intermediate future and distant future ECHAM5 climate scenarios

Quinary Number	Standard Deviation (m^3) Present	Standard Deviation (m^3) Intermediate	Standard Deviation (m^3) Future	I: P	F: P	F: I
4846	5065	5562	6866	1.10	1.36	1.23
4847	13187	14441	18939	1.10	1.44	1.31
4848	556968	555275	701160	1.00	1.26	1.26
4906	22994	34258	43446	1.49	1.89	1.27
4907	33887	50618	64942	1.49	1.92	1.28
4908	1218130	1455606	2277062	1.19	1.87	1.56
5020	5840	9624	11384	1.65	1.95	1.18
5021	17211	27833	33306	1.62	1.94	1.20
5022	299336	673227	1088828	2.25	3.64	1.62
5041	8961	20878	25036	2.33	2.79	1.20
5042	28318	60000	71345	2.12	2.52	1.19
5043	481763	1101827	1637450	2.29	3.40	1.49
5068	5660	13932	14863	2.46	2.63	1.07
5069	23253	51975	55216	2.24	2.37	1.06
5070	2374342	4212677	6146886	1.77	2.59	1.46

Table 14.6 A summary of coefficients of variation (%) of accumulated annual streamflows for the 15 selected Quinary Catchments derived from present, intermediate future and distant future ECHAM5 climate scenarios

Quinary Number	Coefficient of Deviation (%) Present	Coefficient of Deviation (%) Intermediate	Coefficient of Deviation (%) Future	I: P	F: P	F: I
4846	43.83	31.27	28.42	0.71	0.65	0.91
4847	47.54	33.37	31.96	0.70	0.67	0.96
4848	41.62	27.33	25.59	0.66	0.61	0.94
4906	45.49	45.51	41.16	1.00	0.90	0.90
4907	46.42	46.32	42.08	1.00	0.91	0.91
4908	39.67	30.24	32.41	0.76	0.82	1.07
5020	49.22	56.26	52.37	1.14	1.06	0.93
5021	51.38	57.30	54.13	1.12	1.05	0.94
5022	30.96	44.26	44.07	1.43	1.42	1.00
5041	48.31	58.36	53.42	1.21	1.11	0.92
5042	55.35	60.04	54.12	1.08	0.98	0.90
5043	32.96	46.03	43.87	1.40	1.33	0.95
5068	42.32	50.05	37.62	1.18	0.89	0.75
5069	43.03	48.39	36.35	1.12	0.84	0.75
5070	32.15	35.71	35.30	1.11	1.10	0.99

remaining relatively constant (a ratio of close to unity) compared to the C_v s for the present ECHAM5 scenario. The ratio comparison actually shows a slight decrease in C_v s for the distant future to present and distant future to intermediate ECHAM5 climate scenarios. It can thus be concluded that while the absolute variability, expressed through the standard deviation, is increasing markedly for accumulated annual streamflows, the relative variability, expressed through the C_v , is remaining relatively constant or even decreasing in the intermediate and more distant future because the means are increasing at a rate equal to or faster than the variability. The standard deviation ratio analysis for

accumulated annual streamflows also displays a regional trend which indicates an increase in standard deviations over time as one moves from the higher rainfall western to the lower rainfall central and eastern regions of the Thukela Catchment.

14.5.2 Variations in accumulated catchment streamflows between the Quinaries making up a Quaternary Catchment for a single climate scenario

The second method used to describe how accumulated catchment streamflows vary over time explores the flow differences between the three altitudinally defined Quinaries (Upper, Middle and Lower; cf. **Chapter 6**) of a Quaternary Catchment, for a single ECHAM5 climate scenario. **Figures 14.20-14.22** display time series for Quaternary V11JE located in the upper west region of the Thukela Catchment, and results are typical of time series by this method of analysis, with all 15 selected catchments following the same overall trend. **Figures 14.20-14.22** immediately show an inherent problem with this method of time series analysis for accumulated streamflows, with flows from the Lower Quinary (in this case 4848) always showing significantly larger streamflow magnitudes because its streamflow volume equals the total summed streamflows from its own area plus the contributions of upstream subcatchments, in this case Quinaries 4846 and 4847. This accumulation results in a scaling problem, resulting in the plot to only be able to display the streamflow variation of the lower Quinary catchment. A comparison of **Figures 14.20-14.22** does, however, reveal that accumulated streamflows are projected to increase significantly for both the intermediate and distant future ECHAM5 climate scenarios for the Lower Quinary (4848).

14.5.3 Conclusions on time series analyses of accumulated catchment streamflows

The method used to assess projected changes in accumulated annual streamflows from a single Quinary Catchment with climate change indicates that both streamflow magnitudes and their absolute variabilities (i.e. standard deviations) are likely to increase in the intermediate (2046-2065) and more distant (2081-2100) futures while the relative variability (i.e. C_v) is likely to remain the same or even decrease slightly over these time periods. The graphical plots used to illustrate volumetric differences

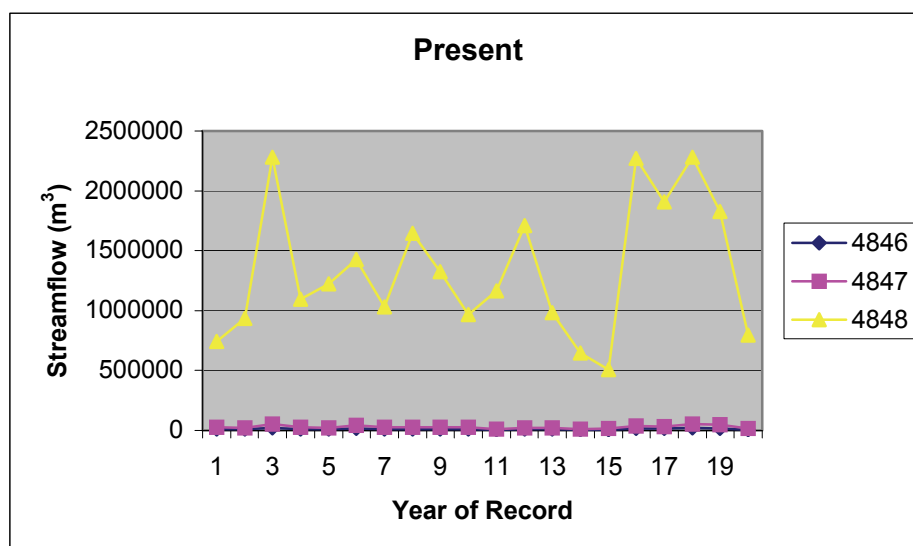


Figure 14.20 A time series of accumulated annual streamflows (m^3) for Quinaries 4846, 4847 and 4848 of Quaternary Catchment V11J derived from the present ECHAM5 climate scenario

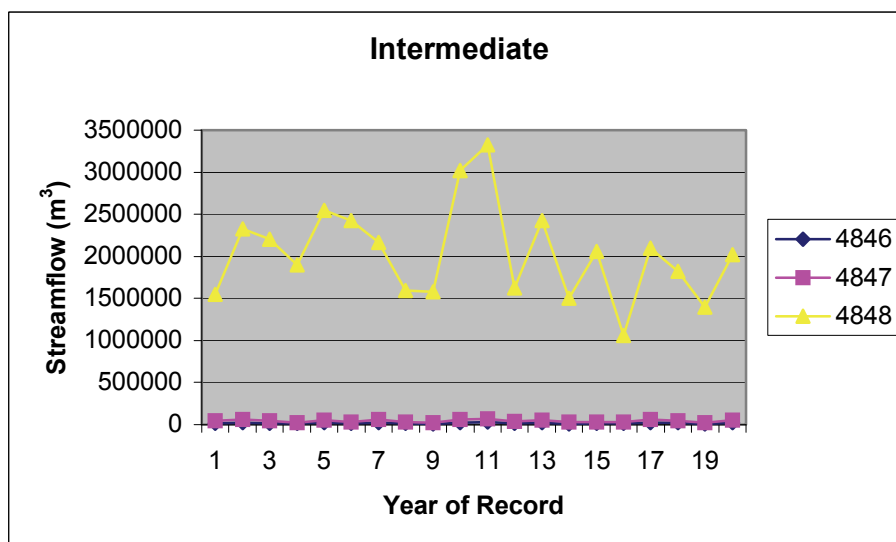


Figure 14.21 A time series of accumulated annual streamflows (m^3) for Quinaries 4846, 4847 and 4848 of Quaternary Catchment V11J derived from the intermediate future ECHAM5 climate scenario

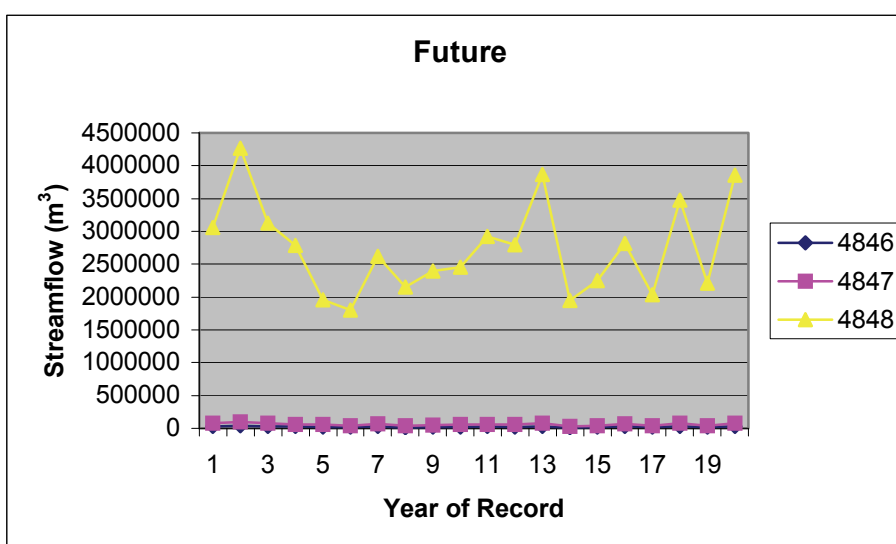


Figure 14.22 A time series of accumulated annual streamflows (m^3) for Quinaries 4846, 4847 and 4848 of Quaternary Catchment V11J derived from the distant future ECHAM5 climate scenario

in accumulated catchment streamflows between the Quinaries making up a Quaternary Catchment for a single climate scenario are not ideal, owing to accumulation and scaling issues, but they nevertheless display significant flow increases for future climate scenarios from the ECHAM5 GCM which are likely to have important implications in water temperature simulations with future climate scenarios.

14.6 Time Series Analyses of Mixed Maximum Water Temperatures

14.6.1 *Projected changes in mixed maximum water temperatures in a single Quinary Catchment with climate change*

The results produced by the time series analysis in the foregoing sections all indicate that there is likely to be a significant increase in mixed maximum water temperature (MMWT) under the projected future climate change scenarios from the ECHAM5 GCM for all the selected Quinaries. These results are expected as MMWT is based on a combination of air temperature (**Section 14.3**) and accumulated streamflow (**Section 14.5**) and both these indicated likely increases under future climatic conditions projected by ECHAM5. This projected increase in MMWT is illustrated in **Figures 14.23-14.27** by way of time series plots from selected Quinaries, with these plots sharing the same y-axis scale for ease of comparison.

Each of the five plots in **Figures 14.23-14.27** represents the Upper Quinary from each of the different regions within the Thukela Catchment. By comparing results from **Figures 14.23-14.27** one can determine how spatial location can influence the temporal characteristics of MMWT. By comparing MMWT for each ECHAM5 climate scenario it can be concluded that MMWT increases as water cascades from the cooler higher altitudes towards the warmer coastal catchments. The MMWTs of the two Quinaries located in the higher altitudes (4847 and 5021) are in the order of 2°C lower than those of the Quinary located near the coast (5069) for all three ECHAM5 climate scenarios.

Figure 14.23 shows a time series of MMWT for Quinary 4847, located in the high altitude upper western part of the Thukela. MMWT is shown to remain relatively constant over the 20 years of a climate scenario, but there are significant differences between the three ECHAM5 scenarios. However, as in the case of air temperature, closer perusal of the time series indicates a rising MMWT trend over the 20 year period of record in both the intermediate and distant futures, which is not visible in the present climate scenario. The MMWT derived from the present ECHAM5 climate scenario for Quinary 4848 (**Figure 14.20**) is approximately 18°C, with this value increasing to approximately 21°C for the intermediate future ECHAM5 climate and finally to around 24°C for the more distant future ECHAM5 climate. Essentially MMWT is thus projected to increase significantly over time, with water temperature values from the present ECHAM5 climate being the lowest, those from the future ECHAM5 climate being the highest and those from the intermediate ECHAM5 being somewhere between these two. This increasing trend and magnitude of change in MMWT between the three ECHAM5 scenarios was found in all 15 selected Quinaries evaluated and can be observed in the remaining four time series plots for this section (**Figures 14.24-14.27**).

14.6.2 *Variations in mixed maximum water temperature between the Quinaries making up a Quaternary Catchment for a single climate scenario*

The second method used to describe how MMWT varies over time explores how water temperature fluctuates between the three altitudinally defined Quinaries (Upper, Middle and Lower; cf. **Chapter 6**) of a Quaternary Catchment, for a single ECHAM5 climate scenario. **Figure 14.28** shows typical time series from this method of analysis, and all 15 selected catchments which underwent this analysis illustrated the same overall trends. **Figure 14.28** shows that the Upper Quinary catchment (4906) of Quaternary V14E has the lowest MMWTs compared to those of the middle (4907) and lower altitude Quinary (4908), with the latter experiencing the highest MMWT. In terms of flow routing, water from Quinary 4906 flows into Quinary 4907, the combined water of which in turn flows into the bottom Quinary 4908. As the water flows downstream to lower altitudes it tends to warm and this is illustrated

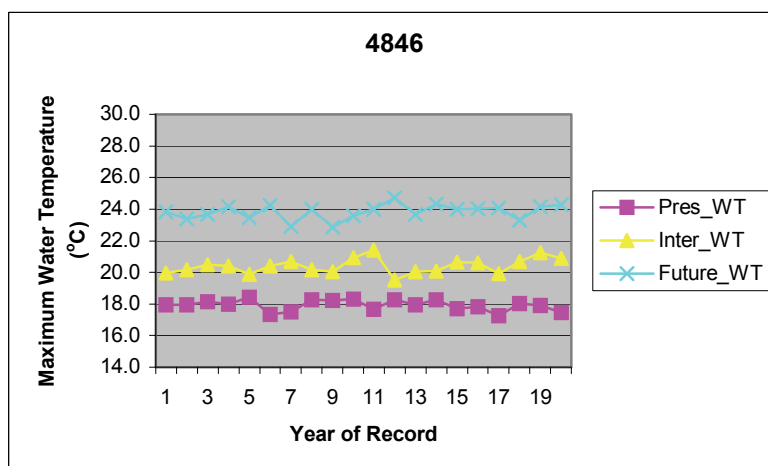


Figure 14.23 A time series of mixed maximum water temperature (°C) for Quinary 4846 of Quaternary Catchment V11J derived from present, intermediate future and distant future ECHAM5 climate scenarios

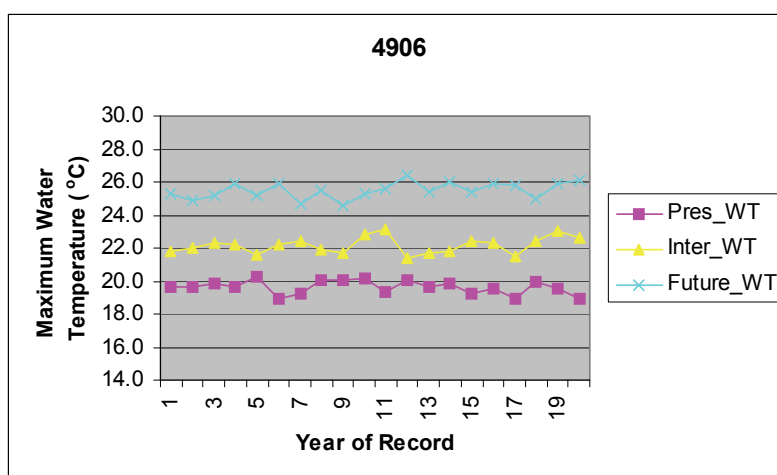


Figure 14.24 A time series of mixed maximum water temperature (°C) for Quinary 4906 of Quaternary Catchment V14E derived from present, intermediate future and distant future ECHAM5 climate scenarios

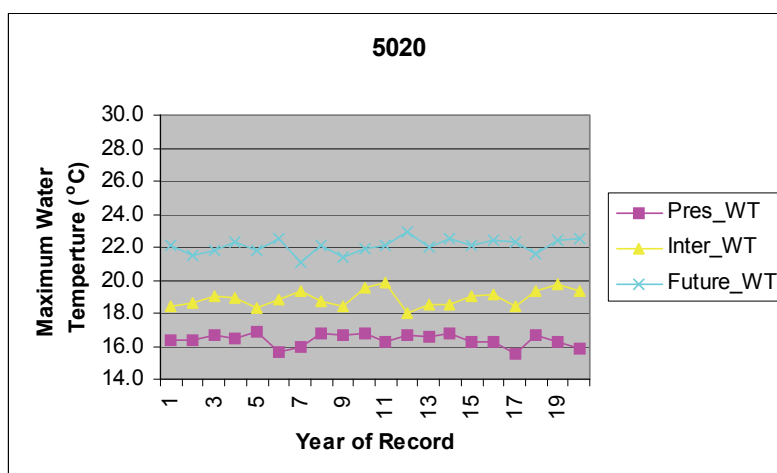


Figure 14.25 A time series of mixed maximum water temperature (°C) for Quinary 5020 of Quaternary Catchment V32B derived from present, intermediate future and distant future ECHAM5 climate scenarios

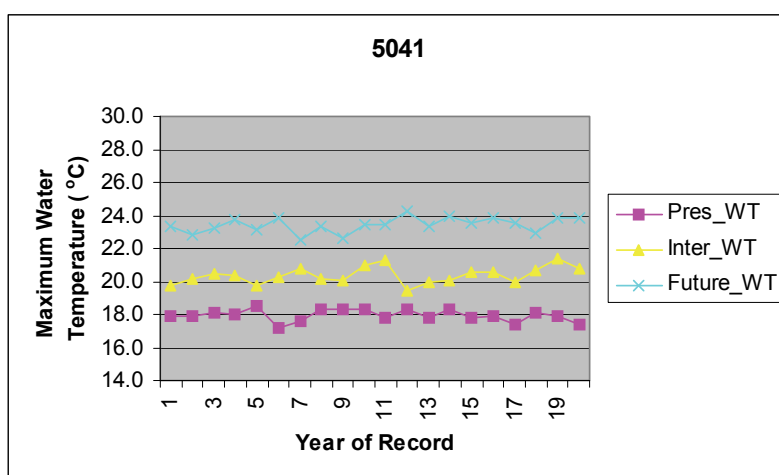


Figure 14.26 A time series of mixed maximum water temperature (°C) for Quinary 5041 of Quaternary Catchment V33A derived from present, intermediate future and distant future ECHAM5 climate scenarios

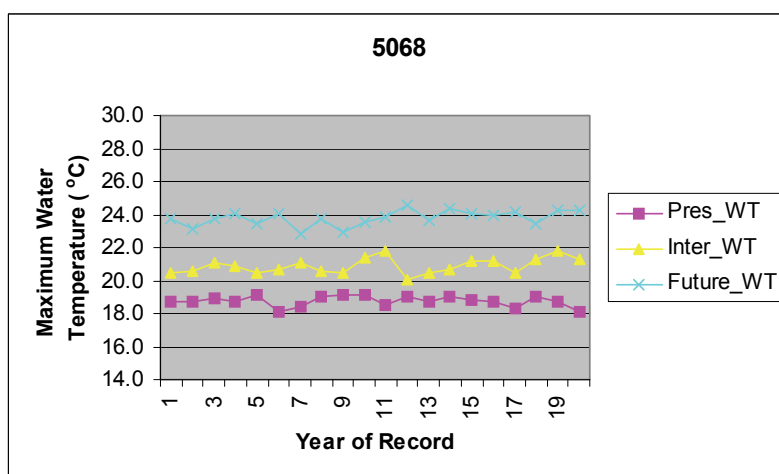


Figure 14.27 A time series of mixed maximum water temperature (°C) for Quinary 5068 of Quaternary Catchment V50A derived from present, intermediate future and distant future ECHAM5 climate scenarios

in the respective times series. This analysis also indicates that all three hydrologically linked Quinaries within a Quaternary Catchment are situated in close proximity to one another, as they all experience the same year-to-year fluctuations of MMWT. If there is therefore a warm year all three Quinaries will show a corresponding increase in MMWT. If one compares **Figures 14.28-14.30** it is noted that there is a definite increase in MMWTs from one ECHAM5 climate scenario to the next for all Quinary Catchments.

By comparing results in **Figures 14.28-14.30** there appears to be an increased inter-annual variation in MMWT from one climate scenario to the next into the future. For example, the present ECHAM5 climate scenario's MMWT (**Figure 14.28**) is reasonably stable with some inter-annual variation over the 20 year record, compared with MMWTs of the intermediate and distant future ECHAM5 climate scenarios (**Figures 14.29** and **14.30**), which project higher variations and many more spikes in MMWT

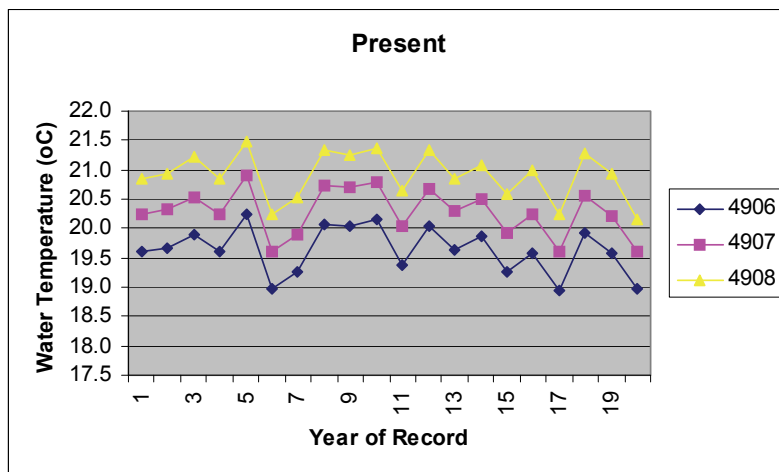


Figure 14.28 A time series of mixed maximum water temperature (°C) derived from the present ECHAM5 climate scenario for Quinaries 4906 (Upper), 4907 (Middle) and 4908 (Lower) of Quaternary Catchment V14E

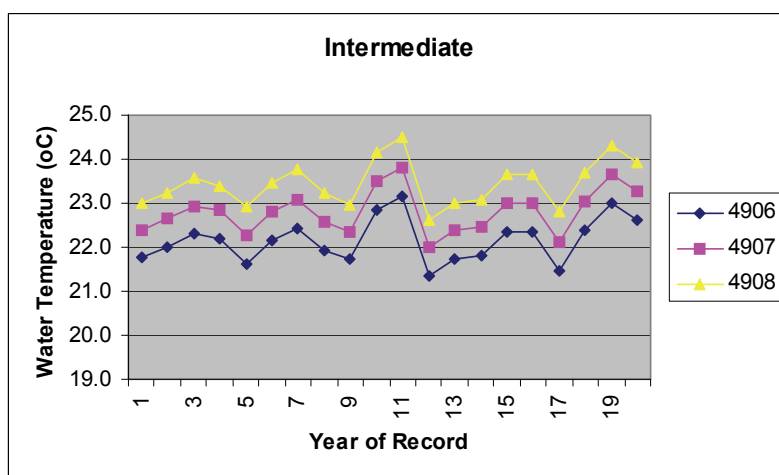


Figure 14.29 A time series of mixed maximum water temperature (°C) derived from the intermediate future ECHAM5 climate scenario for Quinaries 4906 (Upper), 4907 (Middle) and 4908 (Lower) of Quaternary Catchment V14E

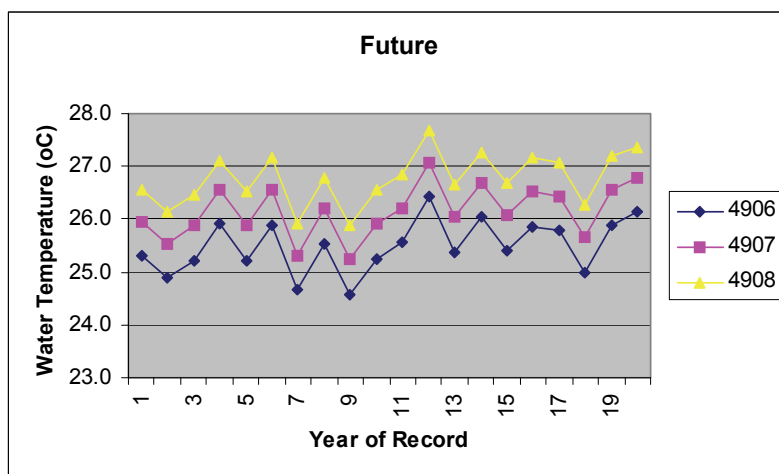


Figure 14.30 A time series of mixed maximum water temperature (°C) derived from the distant future ECHAM5 climate scenario for Quinaries 4906 (Upper), 4907 (Middle) and 4908 (Lower) of Quaternary Catchment V14E

from one year to the next. As already alluded to in previous sections, an increase in the inter-annual variabilities of future MMWTs is an important ecological issue and can be quantified by calculating the standard deviation of the annual MMWTs for the three ECHAM5 climate scenarios (**Table 14.7**). These results support the visual conclusions from the graphical analysis that, like air temperature and streamflow, the variability of MMWT is increasing in the intermediate and distant futures. From **Table 14.7** standard deviations for the intermediate and future ECHAM5 climate scenarios are increasing by an average of 39 and 29% respectively when compared to those of the present ECHAM5 scenario - a result which is similar to that of the standard deviation of air temperature (**Table 14.2**). Furthermore, as in the case of air temperature, there does not seem to be a regional trend in the magnitudes of standard deviations. Ultimately annual MMWT is projected to fluctuate far more in the intermediate and distant futures than under present climatic conditions with the ECHAM5 model, and this increase in variability could very well have serious implications for aquatic species and the management of these ecosystems.

Table 14.7 A summary of standard deviations (°C) of annual mixed maximum water temperatures for the 15 selected Quinary Catchments derived from present, intermediate future and distant future ECHAM5 climate scenarios

Quinary Number	Standard Deviation (°C) Present	Standard Deviation (°C) Intermediate	Standard Deviation (°C) Future	I: P	F: P	F: I
4846	0.34	0.48	0.47	1.42	1.39	0.98
4847	0.35	0.49	0.46	1.42	1.32	0.93
4848	0.35	0.49	0.46	1.42	1.34	0.94
4906	0.40	0.51	0.50	1.26	1.24	0.98
4907	0.40	0.51	0.50	1.26	1.24	0.98
4908	0.40	0.51	0.49	1.29	1.22	0.95
5020	0.38	0.50	0.45	1.32	1.18	0.89
5021	0.38	0.50	0.45	1.32	1.18	0.89
5022	0.39	0.52	0.46	1.31	1.17	0.90
5041	0.36	0.52	0.46	1.44	1.27	0.88
5042	0.35	0.50	0.45	1.46	1.31	0.90
5043	0.36	0.52	0.46	1.43	1.26	0.88
5068	0.31	0.48	0.47	1.54	1.52	0.99
5069	0.30	0.44	0.41	1.46	1.37	0.94

14.6.3 Conclusions on time series analyses of mixed maximum water temperatures

In conclusion, both methods used to describe how MMWT varies over time and space indicate that mean annual MMWT and its variability are likely to increase in the intermediate (2046-2065) and more distant (2081-2100) futures when derived from the ECHAM5 GCM. Furthermore, there is a noticeable difference in MMWT within a single Quaternary Catchment due to hydrological flow routing, with an increase in water temperatures as the water cascades downstream from higher altitude Upper Quinaries to Lower Quinaries at lower altitudes. In both cases the hypotheses set out in **Section 14.1** have thus been confirmed.

14.7 References

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CHAPTER 15 SUMMARY OF FINDINGS ON ECO-HYDROLOGICAL INDICATORS AND RECOMMENDATIONS FOR FUTURE RESEARCH

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Anthropogenic emissions of greenhouse gases have already produced a discernible human footprint on the world's climate, as shown by the historical climate record. This change in climate, which has also been observed in South Africa, is both long term and is accelerating and, as a result, has identified the need to determine the possible effects of climate change on aquatic ecosystems. Freshwater environments are just one type of ecosystem which are likely to be affected detrimentally by rising temperatures, changing precipitation patterns and increasing carbon dioxide levels associated with anthropogenically driven climate change. Over recent years there has been a large increase in amount of literature and studies which have focussed on the potential impacts of climate change on aquatic ecosystems. In this concluding chapter, the aims and objectives of the research will be revisited, thereafter a summary and conclusions are presented and, finally, recommendations for future research will be made.

15.1 Aims and Objectives Revisited

The aims of this component of the project were to:

- conceptualise the higher order impacts of projected climate change on environmentally related streamflow and water temperature indicators in southern Africa,
- utilise a finer spatial scale of investigation and apply output from more advanced climate models than employed in previous climate change impact studies in southern Africa, as input into an appropriate hydrological model, and
- simulate and map the magnitude and direction (positive or negative) of changes of these indicators at a high spatial resolution over southern Africa.

15.2 Summary of Findings

In order to conceptualise the higher order impacts of projected climate change on environmentally related streamflows and relevant water temperature parameters in southern Africa, a review of the relevant literature was conducted. This review focussed on conceptualising aquatic ecosystems within the context of climate change (**Chapter 2**) and on employing eco-hydrological indicators to assess the impacts of climate change. The indicators selected were a small subset of the 67 so-called Indicators of Hydrological Alteration (**Chapter 3**) and water temperature (**Chapter 4**).

A scale dilemma was identified and problems associated with modelling climate change impacts at the scale of Quaternary Catchments were outlined. In order to address this dilemma it was concluded that there was a need to sub-delineate Quaternary Catchments into smaller, more detailed and hydrologically homogeneous response zones (**Chapter 6**). A new method delineates a Quaternary Catchment into three altitudinally defined Quinary Catchments. The RSA, Lesotho and Swaziland have now been delineated into 5 838 hydrologically interlinked and cascading Quinaries (**Chapter 7**) and a Quinary Catchments Database has been established. This finer scale of investigation was employed in this research project to provide greater spatial detail of hydrological responses than in previous

climate change impact studies in southern Africa. The ECHAM5/MPI-OM GCM (abbreviated to ECHAM5) was selected to simulate present and future projected climatic conditions for this research (**Chapter 9**) and was one of the models used in the IPCC's Fourth Assessment Report. The ECHAM5 GCM is a relatively recent climate model with the first results obtained from this GCM having been published in 2005. The ECHAM5 GCM was selected because it projects future climate changes over southern Africa near the middle of the range of "wetter" and "drier" GCMs and by 2008 when model runs for this project were undertaken, was the only downscaled GCM configured hydrologically at the level of detail required by this project. Even though this project utilised one of the latest GCMs international literature still concludes that there are still major uncertainties regarding GCM output and its regional significance. As such the results from this research should be viewed in the light of being within a range of possible outcomes.

The ecological indicators selected were simulated using the individual subcatchment runoff and accumulated streamflow outputs from the *ACRU* agrohydrological modelling system (**Chapter 8**), driven by downscaled daily climate variables from the ECHAM5 GCM for present, intermediate future and more distant future climate scenarios. The subset of Indicators of Hydrological Alteration focussed on the magnitudes and durations of flows and a spatial assessment of how these indicators are projected to change was performed (**Chapter 10**). However in order to fully describe a South African river's flow regime, climate change responses from all 67 indices should be modelled. The final indicator selection was based on the ease of calculation and availability of data. The main findings of **Chapter 12** are summarised below:

The spatial assessment is performed for the 5 838 hydrologically interlinked and cascading Quinary Catchments which constitute the southern Africa study region. The first half of **Chapter 12** focuses on the magnitude of flows, and the ECHAM5 GCM projects the magnitude of both annual subcatchment runoff and accumulated streamflows to increase in the eastern parts of southern Africa for the intermediate future climate scenario, with this wetting signal strengthening in the distant future climate scenario. A band of Quinaries running roughly from the Limpopo Province through to the Eastern Cape Province indicate a decrease in both subcatchment runoff and accumulated streamflows in the intermediate future, while this band of Quinaries is projected to shift westwards to cover the southwestern parts of the Western Cape Province in the distant future climate scenario. The ratio maps for the CoD of both annual subcatchment runoff and accumulated streamflows under projected future climates do not display clear spatial trends. Surprisingly, the Quinary Catchments in the Northern Cape Province display unusually high runoff for such a semi-arid part of southern Africa. The cause of this apparent anomaly is that the unit used to measure flow magnitude, viz. $\text{m}^3 \cdot \text{s}^{-1}$, is a function of catchment area and the areas of these Quinaries are among the largest in the study region and hence the relatively large magnitudes of flow there. These results build on previous climate change studies and provide additional scientific techniques and workable scientific results which could aid decision makers involved in ecological and water management planning.

The second half of **Chapter 12** focuses on the duration of flow events by exclusively using accumulated streamflow for the 1, 3, 7, 30 and 90 day flow durations for both low and high flows, and in terms of flow duration the ECHAM5 GCM projected an overall increase in minimum flows for all flow durations, especially on the eastern side of South Africa. The Western Cape is the major exception and this ratio analysis indicates a distinct decrease in flows with the ECHAM5 GCM of between 5 and 25% for all minimum flow durations for this

region. The ratio maps from the distant future to present ECHAM5 climates show that virtually all Quinary Catchments are projected to experience an increase in their maximum annual accumulated streamflows for all flow durations. The Western Cape is again the major exception and, as in the case of the minimum flow ratio analysis, displays a distinct decrease in maximum averaged annual flows of between 5 and 25% for all flow durations. The ECHAM5 CoD ratio analyses for the minimum and maximum 1, 3, 7, 30 and 90 day average of annual accumulated streamflows does not display clear overall trends or definitive spatial patterns.

Water temperature related parameters (**Chapter 4**) are analysed both spatially and temporally at the scale of the Thukela Catchment (**Chapter 5**). In **Chapter 13** a spatial assessment was made of the potential impacts of climate change on the water temperature related parameters using the baseline climate conditions and the ECHAM5 climate scenarios. This spatial assessment was performed for the 258 hydrologically interlinked and cascading Quinary Catchments, which constitute the Thukela Catchment. In this chapter a series of maps is used to spatially analyse air temperature, individual catchment runoff, accumulated streamflows, mixed maximum water temperature and two water temperature indices. The results and techniques developed in this report culminate in the first real attempt to map potential changes in water temperature variables under conditions of climate change. The techniques developed to assess the impact of projected climate change on the water temperature parameters produced workable results and thus it is recommended that a study covering southern Africa be performed. A summary of the main findings from **Chapter 13** is provided below.

With respect to mean air temperature the spatial analysis shows that there is a close correlation between the MAT from historical air temperature data and that simulated from the ECHAM 5 GCM. A comparison between the ECHAM5 scenarios indicates a strong warming trend over time, particularly in the central parts of the Thukela Catchment, with the ECHAM5 distant future climate scenario showing the greatest deviation from that of the present climate. The reason for the distant future to present ratio map showing the greatest change is that the present climate scenario time period (1971-1990) and the future climate scenario time period (2081-2100) are 110 years apart, from the commencement of their respective simulation periods - this compared with the difference between the intermediate and future climate scenarios only being 35 years from the start of their respective simulation periods, and this trend was found to be consistent for all water temperature related parameters.

The spatial analysis of runoff from individual subcatchment indicates that there could be a marked increase in projected annual subcatchment runoff, with the distant future scenario showing the greatest change compared to that of the present ECHAM5 climate, with most Quinaries showing an increase of between 2 and 3 times compared to that of the simulated runoff from the present ECHAM5 climate.

When comparing accumulated streamflows generated from present baseline climate and the present ECHAM5 climate the results indicate that the simulations are generally closely correlated, with both these scenarios clearly showing the accumulations of streamflows in the major tributaries in Thukela Catchment. As with subcatchment runoff, all ECHAM5 scenarios indicate that there will be substantial increase in accumulated streamflows under projected future climate conditions.

In regard to mixed maximum water temperature, these results follow similar trends to those found in the air temperature and accumulated streamflow analyses. A comparison between the MMWT simulations from the three ECHAM5 climate scenarios reveals a definite increase in MMWT under conditions of projected climate change. The difference between distant future and present ECHAM5 climates contains the greatest increase in MMWT, with most of the Quinaries showing increases of around 5°C, but with the higher lying subcatchments tending to be more sensitive to projected climate change.

In **Chapter 14** time series analyses are employed in order to temporally assess the potential impacts of climate change on water temperature related parameters in the Thukela Catchment. In total, 15 Quinaries, which make up five Quaternaries, were selected in the Thukela to undergo time series analyses. The main outcomes of **Chapter 14** are summarised below.

Time series analyses were performed on the following parameters:

- Mean Air Temperature (MAT),
- Individual Subcatchment Runoff,
- Accumulated Streamflows, and
- Mixed Water Temperature (MMWT).

The time series analyses uses two methods to describe how each water temperature related indicator varies over time, viz.

- How does an indicator vary for a single Quinary catchment by comparing the three ECHAM5 climate scenarios (i.e. a temporal analysis), with the hypothesis being that in future climates temperatures are increasing and streamflows are changing; and
- How does an indicator vary between the three Quinaries making up a Quaternary Catchment for a single climate scenario (i.e. a spatial analysis), with the hypothesis being that Quinaries within a Quaternary are altitude determined and therefore have influences on temperature, rainfall, hence on runoff and thus also on water temperature patterns.

For air temperature, results from time series analyses indicate that annual means of air temperature and their variability, derived from the ECHAM5 GCM, are likely to increase in future. Furthermore, there is a noticeable difference in air temperature between the three Quinaries within a single Quaternary Catchment due to altitudinal variation. Closer scrutiny of the times series indicates a rising air temperature trend within the 20 years of values in both the intermediate and distant future climates, which is not visible in the present climate scenario.

In regard to individual subcatchment runoff and accumulated catchment streamflows, their absolute variability (i.e. standard deviation) from the ECHAM5 GCM is projected to increase in the intermediate (2046-2065) and more distant (2081-2100) futures, while the relative variability (i.e. CV%) is likely to remain much the same or even decrease slightly over these time periods. There is a noticeable difference in individual subcatchment runoff within a single Quaternary Catchment due to altitudinal and area variations. However, this analysis technique is not ideal when applied to accumulated catchment streamflows owing to accumulation and scaling issues.

For MMWT, results from time series analyses indicate that mean annual MMWT and its variability are likely to increase in the intermediate (2046-2065) and more distant (2081-2100) futures when derived from the ECHAM5 GCM. Furthermore, there is a noticeable difference in the MMWT within a single Quaternary Catchment due to hydrological flow routing, with an increase in water temperatures as the water cascades downstream from higher altitude upper Quaternaries to lower Quaternaries at lower altitudes.

It may be concluded from the above summaries and analyses of results that the objectives of this research project were met.

15.3 Recommendations for Future Research

During the course of this research project, which focuses on conceptualising and developing techniques to assess projected climate change, numerous issues have arisen, which are suggested as foci of future research. The issues that were identified are summarised below:

- The ECHAM5 GCM was employed as the climate model in this research in order to project likely future climate conditions. The aim of this project was to *develop techniques* to assess eco-hydrologically related impacts on climate change, and thus only one GCM was used. However, projecting into the future is always linked to uncertainties, especially with models as complex as those simulating future climate systems. In order to reduce this uncertainty and assign levels of confidence to results, output from a series of GCMs should be used in order to obtain a probability distribution of, and a level of confidence on, the climate impacts being modelled.
- All *ACRU* model simulations in this research were performed using baseline land cover information, with the reference vegetation being Acocks' (1988) Veld Types (cf. **Chapter 7**). The incorporation of detailed actual land use information and of the water engineered system (e.g. dams, irrigation and return flows) would significantly enhance the usefulness from the *ACRU* model on catchments where crucial real-world decision may need to be made.
- In this research project only a subset of all the available flow indicators was applied with the three climate scenarios. In order to fully describe a South African river's flow regime, climate change responses from all 67 indices should be modelled. Therefore, in future projects investigating the likely impacts of climate change on flow regimes it is recommended that methods and techniques be developed to assess all 67 indices.
- The equation used to estimate maximum water temperature was developed in the Sabie River Catchment, but has been shown to be acceptably robust for other regions in South Africa. However, a regionally co-correlated equation could provide more regionally relevant results. Furthermore, a more complex equation could be employed to estimate maximum water temperature, as the equation in its current form is fully reliant on the accuracy of the mean air temperature data.
- The Thukela Catchment was used as the test catchment for the water temperature related analysis in this research project. The techniques developed to assess the impact of projected climate change on the water temperature parameters produced workable results and thus it is recommended that a study covering southern Africa be performed.
- Ecologists need to interpret the biological implications of these results.