DIALOGUE ON WATER AND CLIMATE TRAINING PACKAGE

MANAGING CLIMATE VARIABILITY AND CLIMATE CHANGE IN WATER RESOURCES

ACRUcons Report 45
November 2003

R.E. Schulze

School of Bioresources Engineering
and Environmental Hydrology
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Pietermaritzburg

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ACRUcons Report No. 45

Final Report to the

INTERNATIONAL SECRETARIAT OF THE DIALOGUE ON WATER AND CLIMATE

on the Project

TRAINING PACKAGE ON WATER AND CLIMATE

Obtainable from

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University of Natal, Pietermaritzburg
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www.beeh.unp.ac.za

International Secretariat
Dialogue on Water and Climate
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2601 DA Delft
The Netherlands

www.waterandclimate.org

***ACRUcons* Report No. 45**

When referencing the report, please cite as in the following example:

Schulze, R.E. 2003. Managing Climate Variability and Climate Change in Water Resources. University of Natal, Pietermaritzburg, RSA, School of Bioresources Engineering and Environmental Hydrology, *ACRUcons Report*, 45. pp 92.

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PREFACE

The International Dialogue on Water and Climate (DWC) is a platform which seeks to bridge the information gaps between the water and climate sectors in order to improve our capacity to cope with, and adapt to, the impacts on water management of increasing climate variability and change. The goal of the Dialogue is to develop a knowledge base, generate widespread awareness, identify policy and management options that build such capacities, learn from the experiences throughout the world, and make this knowledge available to the most affected communities. The DWC commissioned a series of themes and dialogues for further study. One of these was "Education and Training", under the auspices of which the "Training Package on Water and Climate" was to be developed.

The aim of this Training Package is

> *Presentation of state of the art insights and new developments concerning Water and Climate issues, and their implication for water- and water resources management.*

The target group is managers, professionals and scientists involved in the design and implementation of management strategies dealing with water in relation to climate variability and climate change.

The products are a Training Package consisting of lecture materials and notes, exercise materials, software packages and data, as well as background and reference information. The package should allow implementation of the programme on the basis of the materials produced, provided that enough time is allocated for preparation by a trainer with at least some experience and background in the subject area.

The Training Package can be given at 3 levels: 1 day for senior managers/ policy makers, or 2 - 3 days for middle managers. or 2 - 3 weeks for junior managers who could also take the course as a post-graduate module. At each level the course becomes progressively more detailed and simultaneously more practical and hands-on.

The Training Package has been developed by 3 international collaborating partners and has 3 major components, *viz.*

- ***Understanding Climate Change***
  Professor Joe Alcamo
  Center for Environmental Systems Research
  University of Kassel, Kassel
  Germany

- ***Managing Climate Variability and Climate Change in Water Resources***
  Professor Roland Schulze
  School of Bioresources Engineering and Environmental Hydrology
  University of Natal, Pietermaritzburg
  South Africa

- ***Role Play and Belief Networking***
  Professor Han Klein (Co-ordinator)
  UNESCO Institute for Water Education
  Delft
  The Netherlands

This document contains the lecture material for the second component, which is then supplemented by the hands-on exercises during the courses. The bulk of the lecture material is derived from six major references. Each section/sub-section is superscripted by a number 1 to 6, which refers to the relevant reference given below, or by a number 7, where the material is new, or has been sourced elsewhere. The references are as follows:

1. Kabat, P., Schulze, R.E., Hellmuth, M.E. and Veraart, J.A. (Editors) 2003. Coping with Impacts of Climate Variability and Climate Change in Water Management: A Scoping Paper. International Secretariat of the Dialogue on Water and Climate, Wageningen, The Netherlands, *DWC Report* No. DWCSSO-01. pp 99.
2. Schulze, R.E. 2003. The Thukela Dialogue: Managing Water Related Issues on Climate Variability and Climate Change in South Africa. University of Natal, Pietermaritzburg, South Africa, School of Bioresources Engineering and Environmental Hydrology, *ACRUcons Report*, 44. pp 152.
3. Schulze, R.E. 2001. Hydrological Responses at River Basin Scale. University of Natal, Pietermaritzburg, South Africa, School of Bioresources Engineering and Environmental Hydrology, *ACRUcons Report*, 35. pp 102.
4. Appleton, B., Kabat, P., Bates, B., Hellmuth, M.E., Bullock, A., Connor, R., van Schaik, H., Veraart, J.A., Hoff, H., Alcamo, J., Schulze, R.E. and Droogers, P. 2003. Climate Changes the Water Rules: How water managers can cope with today's climate variability and tomorrow's climate change. International Dialogue on Water and Climate, Wageningen, The Netherlands. pp 105.
5. Schulze, R.E. 2000. Transcending scales of space and time in impact studies of climate and climate change on agrohydrological responses. *Agriculture, Ecosystems and Environment*, 82, 185-212.
6. Schulze, R.E. (Editor) 2003. Modelling as a Tool in Integrated Water Resources Management: Conceptual Issues and Case Study Applications. Water Research Commission, Pretoria, South Africa, *WRC Report*, 749/1/03. pp 264.
7. Other references.

MANAGING CLIMATE VARIABILITY AND CLIMATE CHANGE IN WATER RESOURCES: OVERVIEW, OBJECTIVES, APPROACHES

This particular module of the Training Package should follow upon Prof Alcamo's module on "Understanding Climate Change", the main themes of which are

- How does the world's climate system work?
- What are the driving forces of climate change?
- Foreseeing the future: Climate models and climate scenarios, and
- Climate policy: Coming to grips with climate change

Particularly in its practical exercise component, this module complements Prof Klein's module on "Role Play and Belief Networking".

This module on "Managing Climate Variability and Climate Change in Water Resources" consists of lectures, tutorials, discussions and practical exercises to (re-) arouse interest in the significance of climate variability in water resource management, and to create a greater awareness of the potential impacts of climate change and the likelihood of associated enhanced variability that are hypothesised to go along with climate change. An interactive, participative approach is encouraged.

The module is made up of 5 themes, each of which is a chapter in this document:

- In Chapter 1 on *Setting the Scene*, the emphasis is on how climate variability and climate change fit into the "bigger picture" of water resources management in general, but also with regard to sustainability and recommendations from the Johannesburg World Summit on Sustainable Development.

- In the second theme (Chapter 2) on *Climate Variability, Water Resources and Related Issues*, stock is taken of present-day issues of climate variability in water resources. Experiences and truisms on climate variability, which are often overlooked by water managers, and taken mainly from South Africa, are presented. Emphasis is placed on extremes of floods and droughts.

- Chapter 3 on *Climate Change and Water Resources* highlights the mechanisms by which climate change drivers influence hydrological responses, as well as the place of climate change within the overall drivers of water resources. Focus is also placed on scale issues and uncertainties.

- *Coping with, Adaptation to, and Preparation for, the Future* is the theme of Chapter 4. The role of integrated water resources management as the framework for adaptation strategies is stressed, as is that of climate forecasting. A synthesis of coping and adaptation options in water resources is provided, as is a synopsis on which primary, secondary and tertiary impacts of climate change on water resources require urgent research.

- In the *Modelling Exercises on Impacts of Climate Change on Hydrological Processes and Water Resources* (Chapter 5), background to desirable model attributes is given, a model selection is made and case study examples of simulated impacts are illustrated.

The approach taken is NOT one of “we know it all and want to teach you everything”, but rather one of “you as participants have widespread and local on-the-ground knowledge of the implications of climate variability in managing your water resources, and, with some background information we bring, we can focus together on how to cope better with climate variability and develop adaptation strategies in regard to possible climate change impacts”.

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1. SETTING THE SCENE

1.1 WHAT IS CLIMATE VARIABILITY (CV)?[1,2]

Climate variability (CV) refers to variations in the mean state and other statistics (such as standard deviations, the occurrence of extremes, etc.) of the climate on all temporal and spatial scales beyond that of individual weather events. Variability may be due to natural internal processes within the climate system, i.e. internal variability, in which case it is an entirely natural phenomenon, is reversible and non-permanent or to variations in natural or anthropogenic external forcing, i.e. external variability. CV has time scales from

- diurnal (within the course of a day, e.g. time of occurrence of convective thunderstorms), to
- daily (i.e. variations from one day to the next) to
- intra-seasonal (e.g. monthly coefficients of variation), to
- inter-annual (e.g. year-to-year variability) and
- decadal (e.g. persistent sequences of wet years or dry years).

1.2 WHAT IS CLIMATE CHANGE (CC)?[1,2]

Climate change (CC), on the other hand, is irreversible and permanent, and occurs when a trend over time (either positive or negative) is superimposed over naturally occurring variability. It refers to a statistically significant change in either the mean state of the climate or in its variability, persisting for an extended period. Climate change may be due to natural internal processes or external forcings, or to persistent anthropogenic changes in the composition of the atmosphere or in land use (IPCC, 2001; Schulze, 2003). The most commonly cited contemporary example of CC is anthropogenically forced global warming and the associated trends in increased temperature which result from the enhanced greenhouse effect through increased atmospheric emissions of greenhouse gases. The time scale of this CC is decades to centuries and the trend is more likely to occur in steps than linearly over time.

1.3 HOW CAN WE SUMMARISE THE CLIMATE VARIABILITY/CLIMATE CHANGE DILEMMA?[1]

In many parts of the world, variability in climatic conditions is already resulting in major impacts. These impacts are wide ranging, and the link to water management problems is obvious and profound. Climate variability is already being observed to be increasing, although there are still large uncertainties about the link to climate change (IPCC, 2001). Floods, droughts and other extreme climate events add to the major problems water managers face from population growth, urbanisation and land use changes.

Every year they inflict severe damage on humans and the environment in many parts of the world, but particularly so in those so-called “hot spots” where the frequency of occurrence is greater, the sensitivity higher, the devastation more severe or the communities more vulnerable. We can do little to control the timing and intensity of such hazardous events in the short term. What we need to do, and can, is increase our capacity to cope with the extreme climate events, if we increase our knowledge to do so. Anticipated global warming is likely to exacerbate climate variability, and hence hydrological responses.

1.4 HOW DO CLIMATE VARIABILITY AND CLIMATE CHANGE FIT INTO THE “BIGGER PICTURE” OF HYDROLOGY AND WATER RESOURCES?

1.4.1 The DPSIR Concept[3]

If any one aspect characterises catchments it is the juxtapositioning of human impacts on the hydrological regime, and vice versa, which may be conceptualised by the so-called DPSIR model (Table 1.1) in which a changing catchment hydrology and its feedbacks from society is structured in terms of **D**riving forces, **P**ressures, **S**tates, **I**mpacts and **R**esponses (McCartney *et al*., 2000).

Table 1.1 Changing hydrology at the river basin scale structured in terms of the DPSIR (**D**riving forces, **P**ressures, **S**tates, **I**mpacts and **R**esponses) model (adapted from McCartney *et al.*, 2000 by Schulze, 2001a)

Driving Forces	**Pressures** (i.e. causes of hydrological changes)	**States** (of hydrology: past, present, future)	**Impacts** (+ or – results of change)	**Responses** (international, national, local, institutional)
• Inter-seasonal climate variability • Greenhouse gas forcing • Rising population • Rising security expectations • State subsidies and directives • International market forces	• Regional climate change • Local land use change • Channel manipulation (dams, channel modifications) • River basin water management • Rural-urban migration	• Rivers: quantity • Rivers: seasonality • Rivers: quality • Groundwater • Wetlands • Reservoirs • Lakes	• Degradation of ecosystems • Loss of water rights • Increased need for reliable water supply • Amplification of extremes	• Agenda 21 • WSSD • ICM/IWRM as legal instrument • New management strategies • New research directions • Ecosystem rehabilitation • Modelling

- *Driving forces* would include inter- and intra-seasonal climate variability on which may be overlaid anticipated changes through greenhouse forcing, demands of rising population, expectations of increases in food security (in developing economies) and water security and the ever increasingly dominating forces of government subsidies and legal directives as well as international market pushes and pulls which filter down into changing natural hydrological regimes.
- *Pressures*, i.e. causes of hydrological changes, include regional scale climate change of the reversible type (e.g. El Niño events and changes in their frequency and intensity) as well as of the irreversible type (e.g. trend changes in precipitation amounts and variability), land use change through both rural/urban migrations (particularly in developing economies) and agriculture (extent and intensity) together with streamflow changes resulting from river channel manipulation (e.g. impoundments, channel modifications). These pressures have influenced the
- *State* of hydrology, from the past states through the present and into the future ones. The state implies the quantity of water a river carries and its seasonal distribution, as well as its quality in regard to suspended solids, water chemistry and the biological health of the river water. The state also includes that of, for example, wetlands, constructed dams or natural lakes, as well as the level and quality of groundwater.
- *Impacts* are judged as positive or negative environmental, social and economic consequences which may arise from changes of state of the hydrological system or the ecosystem. These include the degradation of the terrestrial and aquatic ecosystems, loss of water rights, the amplification of extreme events or the increased need for reliable water supplies (e.g. with urbanisation).
- *Responses* are societal reactions that attempt to affect either the driving force or the pressures causing changes of state of the hydrological system, effectively acting as a system feedback (McCartney *et al.*, 2000). They can be international (e.g. to statements emanating from Agenda 21 and/or the World Summit on Sustainable Development), national (e.g. by implementation of integrated catchment management as a legal instrument, as in South Africa), local (e.g. through water restrictions) or institutional (e.g. by a bulk water supplier). Responses can, furthermore, mean new water management strategies (e.g. through levies on streamflow reducing activities or the polluter pays principle), new research directions (e.g. on impacts), putting to practice new concepts (such as ecosystem rehabilitation) or the application of hydrological simulation models for near real-time operational decision making.

1.4.2 How does Water Resources Management fit into the sustainability concept?[7]

A literal definition of sustainability would be 'the capacity to continue into the future indefinitely' (Eakins, 1995). Sustainability has been defined from a range of perspectives, which makes the meaning of sustainability dependent on the context in which it is applied, in this case water resources. Sustainability refers to both sustainable development and to sustainable resource use and is generally accepted as a goal that is desirable to achieve. From a plethora of definitions, five major pillars of sustainability emerge (Hurni, 2000), *viz*:

- protection of ecology
- acceptability to society
- economic viability
- economic productivity and
- effectiveness in reducing risk.

All five these pillars of sustainability relate closely to the management of water resources – in the context of this document particularly the last-named point.

1.4.3 Sustainable development and water resources: What have we "inherited"?[3]

How have we, however, managed our water resources to date? Decades of 'conquering' and developing land and water, including the application of technologies such as dam building or inter-catchment transfers to manage adequate supplies of water for society's and agriculture's needs, or solving water quality problems by chemical treatment downstream of waste production rather than upstream at source (Falkenmark *et al*., 1999) has left us with a 'damaged' ecosystem (Newson *et al*., 2000), as illustrated in Figure 1.1.

In this 'damaged ecosystem'

- spontaneous regulatory functions of rivers and their catchment areas have been disturbed (e.g. through deforestation or increased erosion or dam construction), or removed (e.g. by draining of wetlands), thereby causing changes of state of the hydrological system
- while the manner of exploiting water, and the land from which it is generated, has changed through *intensification of water use* (e.g. by irrigation, dryland cropping, urbanisation) on the one hand, and on the other *destruction of traditional exploitation* (e.g. by marginalisation of more traditional land use systems and exploitation of marginal lands),

both signifying impacts of human systems.

Responses to the 'damaged' ecosystem can be through

- reactive responses, e.g. by recommending precautionary actions or rehabilitating damaged elements of the system, or
- proactive responses, in seeking to prevent the destructive causes and adopting a 'least regrets' approach in water management by conserving the natural capital of the broader land/water environment through sustainable development, which in this case of water resources implies the integrated management thereof.

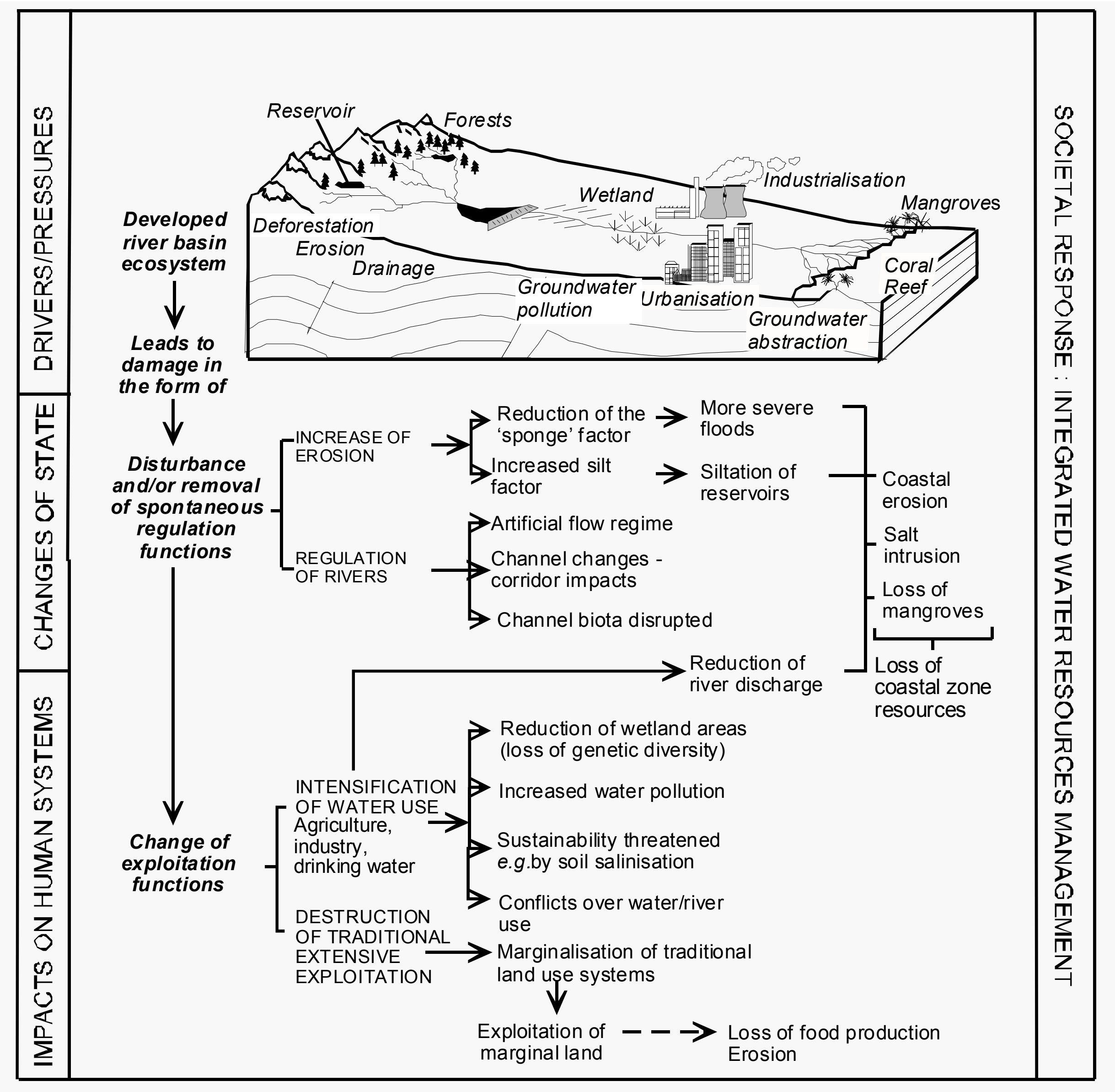


Figure 1.1 The 'damaged' inherited catchment ecosystem within a framework of the DPSIR model, resulting in Integrated Water Resources Management as the societal response (after March and and Toonstra, 1986; Newson, 1997; Schulze 2001)

1.4.4 What did the Johannesburg World Summit of 2002 state on sustainable development and water resources?[7]

The World Summit on Sustainable Development held in Johannesburg in 2002 confirmed its commitment to sustainable development, in particular the Rio principle of common, but differentiated responsibilities, which has important bearing on implementation strategies of adaptation measures in water resources resulting from climate change and possibly enhanced climate variability in future. By this principle

> *States shall co-operate in a spirit of global partnership to conserve, protect and restore the health and integrity of the Earth's ecosystem. In view of the different contributions to global environmental degradation, States have common but differentiated responsibilities. The developed countries acknowledge the responsibility that they bear in the international pursuit of sustainable development in view of the pressures their societies place on the global environment and of the technologies and financial resources they command*.

In regard to sustainable development the WSSD Plan of Implementation makes many specific references to water resources, for example to Integrated Water Resources Management (*inter alia*, in Articles 20, 24, 25, 38, 57, 59, 60, 67, 70, 72 and 91), including promotion of, policy towards and/or strategic plans for

- data, information, monitoring and information systems (Articles 26, 60, 104 and 119)
- capacity building and research in water, including diffusion of technologies and partnerships in research (Articles 24,25, 27, 60, 99, 102, 105, 107, 118, and 119)
- access to safe drinking water (Articles 24, 25 and 60)
- health (Articles 24 and 47)
- ecosystems, e.g. wetlands, environmental protection (Articles 24, 25, 31, 38, 59 and 104)
- agriculture and forestry (Articles 25 and 38)
- desertification (Article 39)
- mountain ecosystems (Article 40) and
- policy instruments (Articles 25, 43, 56 and 60).

1.4.5 What specific focus did the WSSD place on climate variability? And what actions did it suggest?[7]

Focusing directly on climate variability and climate change is Article 35 of the WSSD's Plan of Implementation. Article 35 states:

> *An integrated, multi-hazard, inclusive approach to address vulnerability, risk assessment and disaster management, including prevention, mitigation, preparedness, response and recovery, is an essential element of a safer world in the twenty-first century.*

Actions are required at all levels to:

- Strengthen the role of the International Strategy for Disaster Reduction and encourage the international community to provide the necessary financial resources to its Trust Fund

- Support the establishment of effective regional, subregional and national strategies and scientific and technical institutional support for disaster management
- Strengthen the institutional capacities of countries and promote international joint observation and research, through improved surface-based monitoring and increased use of satellite data, dissemination of technical and scientific knowledge, and the provision of assistance to vulnerable countries
- Reduce the risks of flooding and drought in vulnerable countries by, *inter alia*, promoting wetland and watershed protection and restoration, improved land-use planning, improving and applying more widely techniques and methodologies for assessing the potential adverse effects of climate change on wetlands and, as appropriate, assisting countries that are particularly vulnerable to those effects
- Improve techniques and methodologies for assessing the effects of climate change, and encourage the continuing assessment of those adverse effects by the Intergovernmental Panel on Climate Change
- Encourage the dissemination and use of traditional and indigenous knowledge to mitigate the impact of disasters, and promote community-based disaster management planning by local authorities, including through training activities and raising public awareness
- Support the ongoing voluntary contribution of, as appropriate, non-governmental organisations, the scientific community and other partners in the management of natural disasters according to agreed, relevant guidelines
- Develop and strengthen early warning systems and information networks in disaster management, consistent with the International Strategy for Disaster Reduction
- Develop and strengthen capacity at all levels to collect and disseminate scientific and technical information, including the improvement of early warning systems for predicting extreme weather events, especially El Niño/La Niña, through the provision of assistance to institutions devoted to addressing such events, including the International Centre for the Study of the El Niño phenomenon
- Promote co-operation for the prevention and mitigation of, preparedness for, response to and recovery from major technological and other disasters with an adverse impact on the environment in order to enhance the capabilities of affected countries to cope with such situations.

The above encapsulates the essence of the Dialogue on Water and Climate's endeavours in regard to climate variability and improving adaptation measures.

1.4.6 How has the WSSD focused specifically on climate change? And what actions did it suggest?[7]

Article 36 of the WSSD's Plan of Implementation states:

> *Change in the Earth's climate and its adverse effects are a common concern to humankind. We remain deeply concerned that all countries, particularly developing countries including the least developed countries and small island developing States, face increased risks of negative*

impacts of climate change and recognise that, in this context, the problems of poverty, land degradation, access to water and food and human health remain at the centre of global attention.

Particularly pertinent to this DWC Training Package are the required actions of:

- building and enhancing scientific and technological capabilities…for the exchange of scientific data and information, especially in developing countries and
- supporting initiatives to assess the consequences of climate change…, including the environmental, economic and social impacts on local and indigenous communities.

1.5 WHO ARE WATER MANAGERS AND WHAT DO THEY MANAGE?

1.5.1 What does water resources management (WRM) involve?[1]

For the professional water resources manager, water management involves the regulation, control, allocation, distribution and efficient use of existing supplies of water to offstream uses such as irrigation, power cooling, municipalities and industries, as well as to the development of new supplies, control of floods and the provision of water for instream uses such as navigation, hydro-electric power, recreation and environmental flows.

1.5.2 Who are involved?[1]

All levels of government, as well as the private sector and individual stakeholders, are routinely engaged in the management of water. Hence, technically, every individual who uses water is a water manager, from the water resource professional to the woman in the village who draws water from a well. Those who pay for its delivery and treatment are also responsible for its efficient use and conservation. Nevertheless, water managers typically are considered to be those people who are formally trained and involved in some institutionally organised component of water development, delivery or regulation, and who have responsibility and accountability for the decisions that are made.

For the purposes of this discussion, all users, including farmers, are considered to be water managers. In terms of water resources systems, both the large-scale, mostly technical systems, and the small-scale rural systems (including rainfed agriculture) are taken into account. Addressing the adaptation options that farmers in the lesser-developed countries have is particularly critical, owing to the direct impacts climate variability and change could have on their livelihoods.

1.6 HOW DO WE SUMMARISE THE LINK BETWEEN WATER MANAGEMENT AND CLIMATE?

1.6.1 An introductory statement[4]

Water is inextricably linked with food security, human health and environmental protection. Rapid population growth, increasing urbanisation, industrialisation and pollution threaten the sustainability of our water resources. Natural climate variability and human-induced climate change add to those threats, particularly in developing countries where the impacts are potentially great and the capacity to cope is weakest. Hydrometeorological disasters such as floods and droughts have major effects on food supplies, health, economic and environmental losses, and social upheaval. Economic losses from natural disasters, including floods and droughts, increased three-fold between the 1960s and the 1980s.

1.6.2 The water management link to climate through floods and droughts[4]

Drought is a normal recurring feature of climate. It has many causes, often synergistic in nature. Droughts occur in virtually every climatic zone, but their characteristics vary significantly from region to region. Floods too have multiple causes. They may simply be generated by torrential rains from tropical and extra-tropical cyclones. Though excessive rainfall alone can cause flooding, the most severe riverine floods usually involve a combination of meteorological and hydrological factors. These can include, for example, an earlier unusual sequence of rainfall events (that could have been predicted from short-lead seasonal climate forecasts), saturated soil conditions and high river flows prior to the critical rainfall event(s). New understanding of climate and its variations on seasonal and inter-annual scales, together with a growing ability to predict seasonal phenomena like El Niño, provide new means of reducing our vulnerability and improving our capacity to cope with weather extremes.

1.6.3 What, then, do water managers deal with?[4]

Water managers have to deal with a host of interlinked issues: supply; quality; allocation; distribution; equity with respect to present and future generations; resource vulnerability and reliability; sustainable use; biological diversity; and ecological integrity. For many water managers in developing countries, vulnerability to future climate changes may seem to be a far-away problem. Certainly, many argue for focussing on current pressing issues related to population growth, economic underdevelopment and lack of investment in water infrastructure, rather than on climate change. To some water managers, dealing with natural climate variability and climate-related hazards such as droughts and floods has always been a part of their routine concerns. For them, taking climate change into account does not mean adding any new magic tricks to their present practices for coping with climate extremes (except perhaps in some regions with high vulnerability to climate change, like small islands or low-lying coastal zones). What they do have to recognise is that climate variability is increasing fast and future weather is likely to be more extreme more frequently.

1.6.4 Are adaptation practices in place yet for coping with future climates?[4]

In many countries the good practices of adapting to climate variability are not yet in place. Effective management of climate risks calls for a holistic approach linking technological, social and economic development with the protection of natural ecosystems and with dependable projections of future climatic conditions. There is a need to mobilise expertise across several disciplines to provide the knowledge and methods necessary to assess the climate risk connected with rural and urban water management, and to develop adaptive strategies that can respond to emerging climate fluctuations and help to reduce adverse impacts. The process involves making connections between climate prediction, climate-related hazards, climate change, and the planning, design, operation, maintenance, and rehabilitation of water-related infrastructure.

1.6.5 What balances therefore need to be established?[4]

Establishing balances between consumptive use, environmental needs, subsidiary functions such as flood control, and the ill-defined costs and benefits of climatic impacts on fisheries, aquatic ecosystems, scenery and recreation, is technically complex and subject to a high level of uncertainty. It requires difficult decisions involving the interests of various sectors of the economy, the community and the environment. By taking a pro-active approach, water managers can pre-empt and avoid water crises whenever possible and devise effective responses to crises when they occur. To date, most water managers have adopted a static rather than adaptive approach to setting operating policies. This risk-averse behaviour is often encouraged by the constraints imposed by the political and institutional arrangements and societal expectations. However, increasing demand for water from finite sources will progressively lead to decisions that are more responsive to predicted and forecast climatic conditions and involve a higher degree of uncertainty and risk – as part of the balances which need to be established.

2. CLIMATE VARIABILITY, WATER RESOURCES AND RELATED ISSUES

2.1 TAKING STOCK OF THE PRESENT: CASE STUDIES FROM SOUTH AFRICA

2.1.1 Even when considering average climatic conditions, we live in a high risk environment in South Africa[2]

This statement is borne out by the information in Figure 2.1. For example, mean annual precipitation (MAP), which represents the simplest index of a region's potential water resource, ranges from < 100 mm to over 1200 mm in the legend of Figure 2.1 (top), with a mean of ~ 490 mm. In fact, the rainfall station range is from < 50 to > 3000 mm. This range in MAP has resulted in about one third of South Africa having a mean annual runoff (MAR) less than 10 mm (Figure 2.1, middle; Schulze, 1997a). Indeed, when the rainfall to runoff conversion is considered, over approximately half of South Africa this conversion is < 5% (Figure 2.1, bottom) – a very low percentage when compared to the world mean of 35%. Runoff, defined here as the combined stormflow plus baseflow, has been generated at the scale of Quaternary Catchments, of which 1946 have been delineated in this region, and was computed with the daily time step *ACRU* model (Schulze, 1995).

Numerous factors contribute to this low conversion rate over SA, not least the high level of aridity. This may be expressed as the ratio between mean annual potential evaporation (i.e. atmospheric demand) and MAP. The range from 2 to 20 (Figure 2.2, top) is an indicator that rain will frequently fall on a catchment with low soil moisture, hence with low hydrological response. Adding further to the complexity of the "high risk" hydroclimatic environment is that over most of SA the rainfall is highly seasonal, with strongly defined winter and summer rainfall regions and only a small part effectively receiving rainfall in all seasons (Figure 2.2, middle). The strength of this seasonality becomes more evident still in the map of rainfall concentration (Figure 2.2, bottom), where this index of rainfall distribution displays high values over most areas, indicative that the already seasonal rainfall is concentrated into a few months only. These factors all strongly influence the generation of streamflows and its intra-annual distribution.

2.1.2 An already high inter-annual rainfall variability is amplified by the natural hydrological system[2]

It is the variabilities of rainfall and runoff from year to year, and within a year, rather than the average amounts per se, that cause complexities and uncertainties in water resources management (WRM) and frequently result in water stresses (i.e. too dry or too wet). The simplest index of climate variability is the coefficient of variation (CoV%) of annual rainfall. Large tracts of SA display an inter-annual CoV% > 40% (Figure 2.3, top), which is very high by world standards. Comparison with Figure 2.1 shows a general inverse relationship between CoV(%) and MAP, with the drier areas impacted doubly with the low rainfall compounded by its inconsistency from year to year.

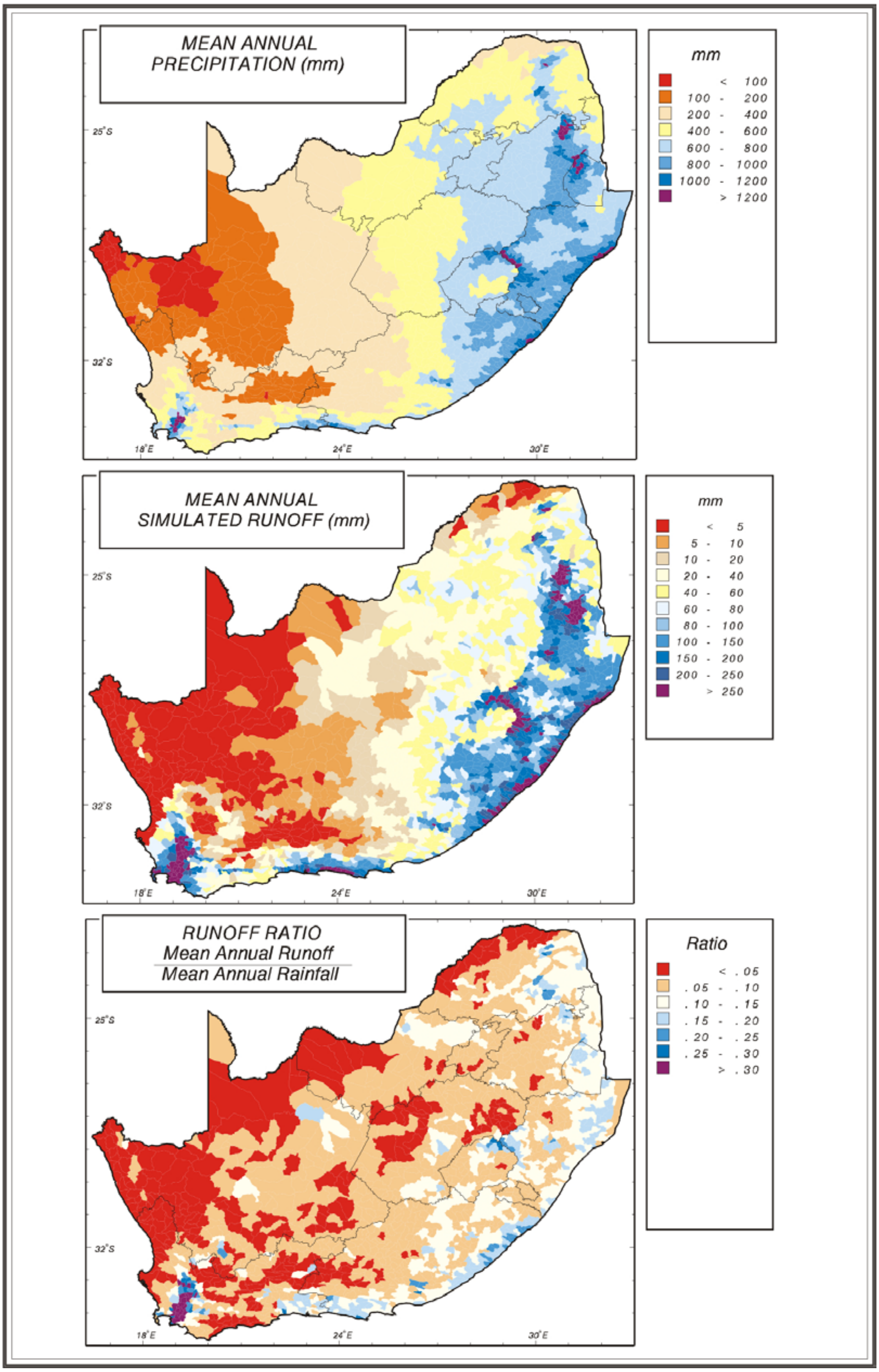


Figure 2.1 Mean annual precipitation (top), mean annual runoff (middle) and the ratio of mean annual runoff to precipitation (bottom) over southern Africa (Source: Schulze, 1997a)

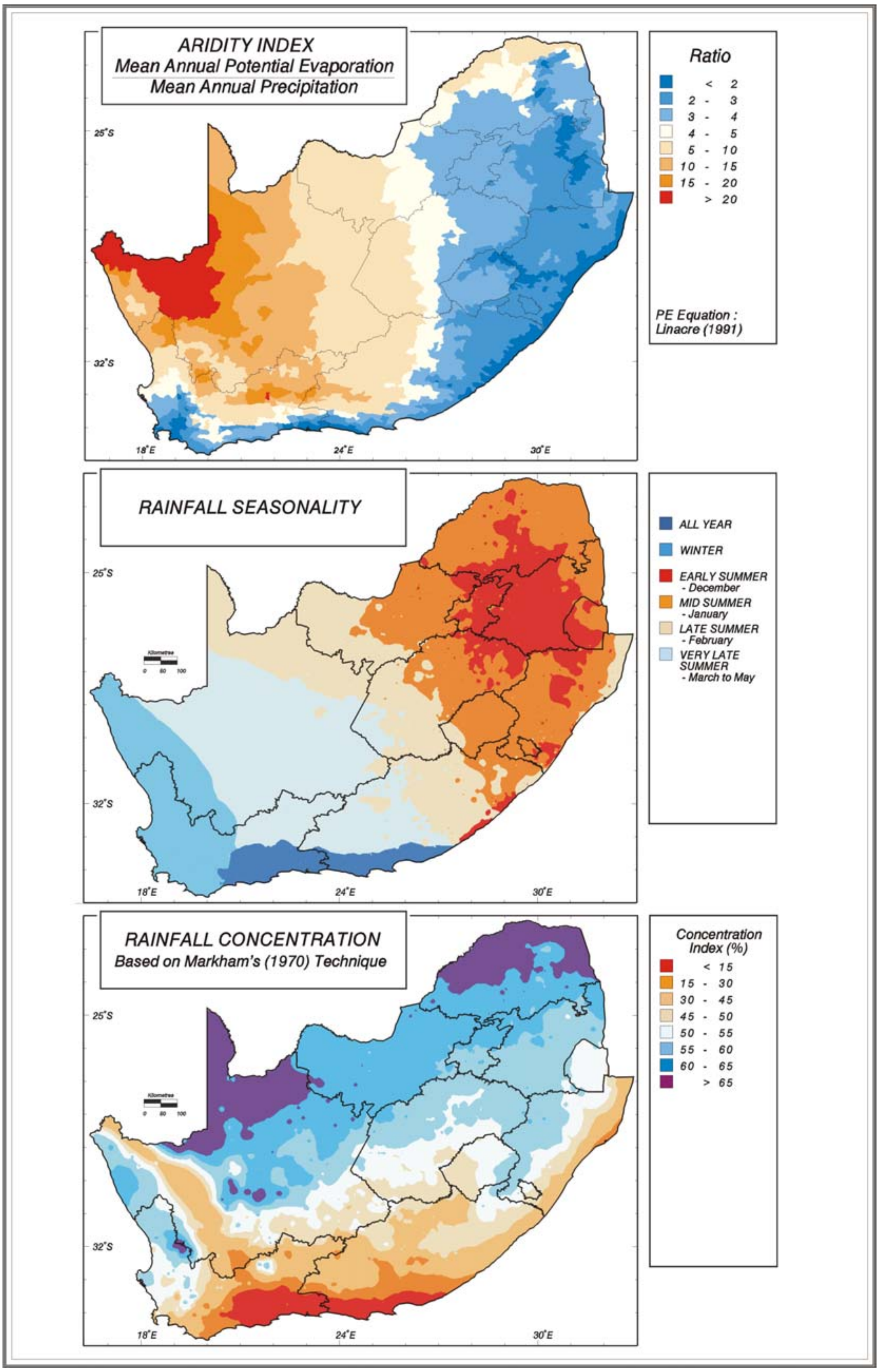


Figure 2.2 Aridity index (top), rainfall seasonality (middle) and rainfall concentration (bottom) over southern Africa (Source: Schulze, 1997a)

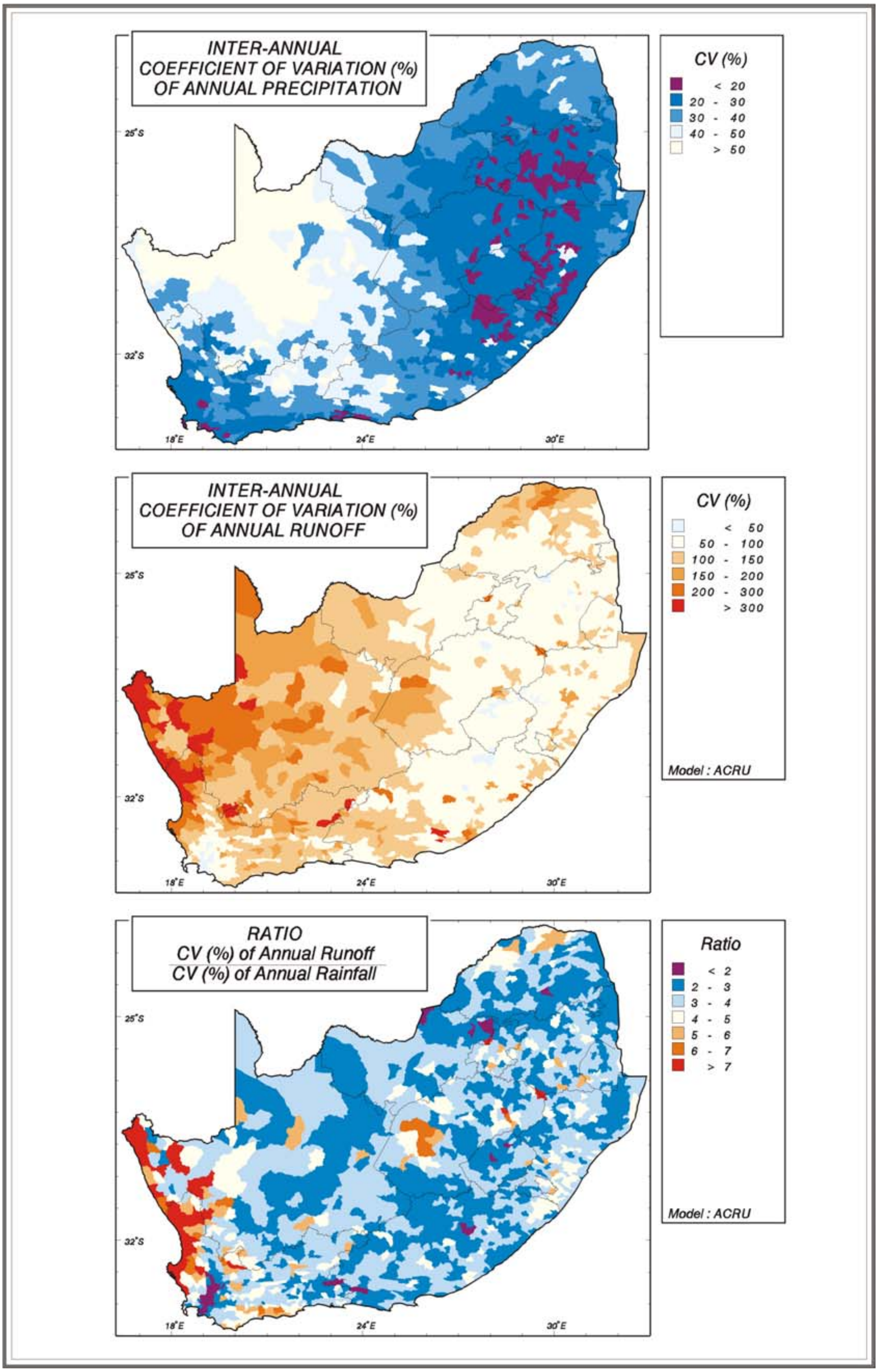


Figure 2.3 Inter-annual coefficients of variation (%) of rainfall (top) and runoff (middle) over southern Africa and the ratio between the two (Source: Schulze, 1997a)

Compared with its rainfall equivalent, the inter-annual CoV% of runoff is highly amplified, with values ranging from 50 – 300% (Figure 3, middle; Schulze, 1997a). This amplification of variability of the natural hydrological system, where "natural" implies no disturbances by land use or channel modification, is well illustrated in Figure 2.3 (bottom), which shows the ratio of CoV% MAR to CoV% MAP to be 2 to 4 and up to 7 - a factor which compounds WRM considerably.

2.1.3 Why does the hydrological cycle amplify the variability in climate?[5]

Hydrological (and ecological, including agricultural) systems are organised hierarchically with many feedbacks occurring across overlapping scale spaces (Harvey, 1997). In both systems, however, some fundamental reasons why hydrological amplification can occur may be isolated. These are discussed below from the perspectives of hydrological responses. Six causes of scale problems with regard to hydrological responses may be identified (Harvey, 1997; Bugmann, 1997):

2.1.3.1 Spatial heterogeneity in surface processes[5]

Natural and anthropogenic landscapes display considerable heterogeneity (or patchiness) which influence the types of processes which dominate and the rates at which they occur. These include the spatial and/or temporal variability of

- *topography*, e.g. altitude, aspect, slope, position in the landscape (be it upland, midslope or footslope);
- *soils*, e.g. their infiltrability, transmissivity or water holding capacity, dependent *inter alia* on geology and topographic position;
- *rainfall*, e.g. its frequency of occurrence, persistence of wet or dry days, duration, intensity, seasonality or total amount;
- *evaporation*, dependent on atmospheric demand (solar radiation, water vapour deficit and wind) in interplay with soil and vegetation characteristics;
- *land use*, accounting for factors such as the leaf area index (LAI) and photosynthetic/stomatal characteristics of actively photosynthesising plants, canopy interception of rainfall, canopy height, structure and root distribution, as well as the degree of imperviousness, and including effects of tillage practice and drainage.

2.1.3.2 Non-linearity in responses[5]

In Figure 2.4, the cross-section of a catchment illustrates the various vertical (both up and down) and lateral fluxes which occur in the natural hydrological system. Clear distinctions in responses are made between hillslope processes (both below and on the surface) and channel processes. Some processes occur episodically (e.g. rainfall), others cyclically (e.g. evaporation), still others ephemerally (e.g. lateral flows) or continually (e.g. groundwater movement). Another perspective is that certain responses are rapid (e.g. surface runoff), others at the time scales of days (e.g. lateral flows) or months (e.g. groundwater movement). These different rates of process responses introduce a high degree of non-linearity to the system, which is exacerbated when the

CATCHMENT HYDROLOGICAL SYSTEM
CROSS SECTION

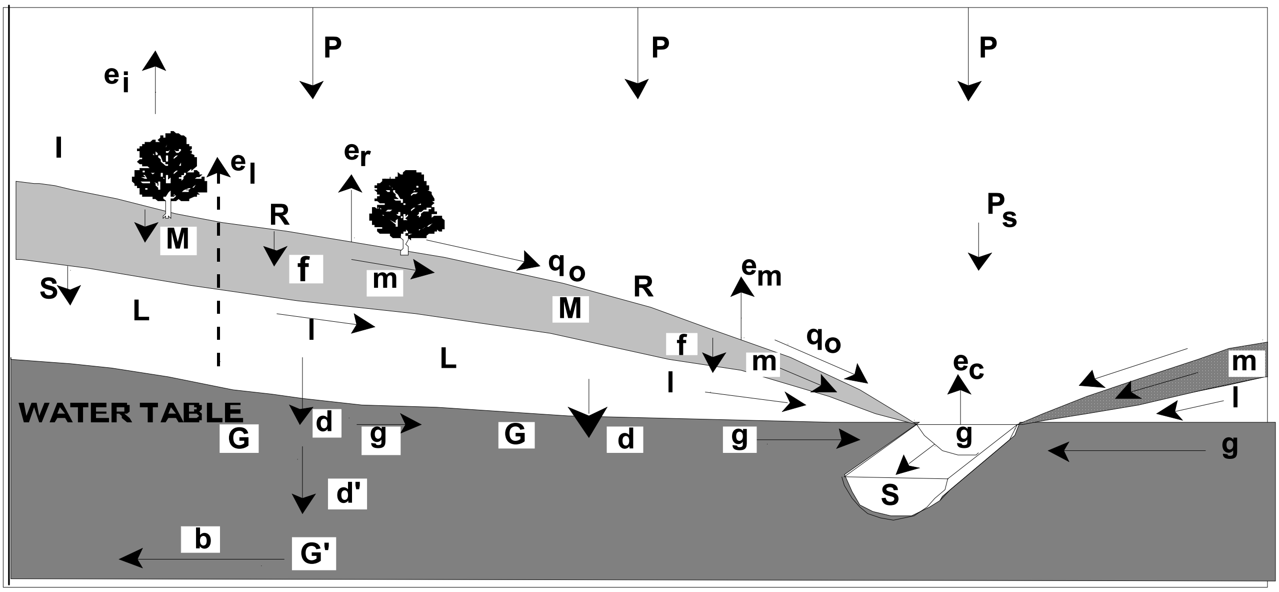


Figure 2.4 Cross-section of a catchment: Fluxes and processes

natural system is replaced by anthropogenic systems such as land use changes or reservoirs, or when climate drivers change.

2.1.3.3 Runoff responses require thresholds to occur[5]

Surface runoff generation, for example, involves two distinct processes each with a different threshold in order to occur. On the one hand, overland flow on high ground at a distance from a channel is a process which occurs at a point in the landscape when rainfall intensity exceeds the infiltration capacity of soil. Saturated overland flow, on the other hand, is an areal process which requires a minimum upslope area over which lateral flows can accumulate and move downslope to saturate the area around the channel, with any rain then falling on the area variably-sized saturated zone being converted to overland flow.

Subsurface flow generation, similarly, consists of two distinct thresholds. In this case, the threshold interflow (i.e. subsurface lateral flow down a hillslope) to occur will depend, *inter alia*, on soil horizonation, different hydraulic conductivities along a hillslope toposequence (e.g. the crest or scarp or midslope or footslope) as well as on slope shape (e.g. concave, convex, uniform). On the other hand, the threshold for baseflow is determined by aquifer properties, the amount of recharge to groundwater that has taken place through either the soil profile or the channel and whether or not the groundwater level is “connected” or “disconnected” to the channel.

The threshold for the generated runoff to flow down a natural channel will be subjugated to hydraulic laws which are determined, *inter alia*, by channel length, shape, roughness and slope. However, these thresholds would be modified markedly by human interventions through dam construction, canalisation or water transfers into or out of the system.

2.1.3.4 Dominant processes change with scale[5]

On small catchments, for example, hillslope processes are influenced by slope, soil and/or land use properties which, together with the occurrences and characteristics of localised small-scale storm events, would largely determine the shape of the hydrograph. On large catchments, on the other hand, the hydrograph shape is often determined largely by hydraulic characteristics of channels and reservoirs as well as by occurrences and properties of large-scale regional rains of frontal and cyclonic origin. This concept is elaborated upon in Section 2.1.4.

2.1.3.5 Development of emerging properties[5]

Emerging properties arise from the mutual interaction of small-scale properties among themselves, for example, edge effects between landscape patches. These have different properties at large scale to the ones displayed by the same patches at small scale. A typical example would be the enhancement of evaporation at the edge of a well-irrigated field surrounded by a dry environment (the so-called “clothesline effect”), while over the irrigated field itself, if large enough, evaporation would be suppressed by a vapour blanket of air with a reduced vapour pressure deficit (the so-called ”oasis effect”).

2.1.3.6 Disturbance regimes[5]

Amplification problems immediately arise as a consequence of disturbance regimes being superimposed over a natural system, for example by climate change or the construction of dams, draining of fields or changes in land use such as agricultural intensification or urbanisation.

2.1.4 More on dominant natural and anthropogenic influences at the catchment scale as a cause of hydrological non-linearities and amplification[3]

Natural heterogeneities occur across a range of spatial scales from hectares to global, but dominate hydrological responses over a narrower spectrum. If the catchment scale is defined spatially as spanning areas in the range of 10^2 to 10^5 km^2 in contrast to the small catchment scale at <10^2 km^2 and the continental scale at > 10^5 km^2, then the conceptual depiction in Figure 2.5 (top) shows that

- *soil*, in terms of texture, depth or drainage properties; or
- *local topography*, with regard to influences of slope, aspect, altitude gradient on microclimate and differential evapotranspiration;

are no longer dominant natural hydrological drivers at this scale. On the other hand,

- *physiography*, i.e. the macro-landscape (with its morphological and/or morphotectonic units such as mountains, plateaux, plains or lowlands), and in phase with that
- *vegetation* (i.e. the broad natural land-cover units which can influence the hydrological regime i.t.o. biomass and its seasonal variation, or aerodynamic roughness), the
- *regional climate* (e.g. precipitation in its various forms, temperature and evaporation patterns as a function of macro-landscape elements and continentality), the
- *waterscape* (including channels, floodplains, wetlands, lakes, estuaries and the associated ecosystems) and, to some extent,
- *macro-climate* (i.e. synoptic scale rainfall generation, or "Grosswetterlagen")

become key variables to a greater or lesser extent at the catchment scale, depending on the hydroclimatic regime (i.e. whether semi-arid, sub-humid or humid).

Similarly, anthropogenic influences also occur across a range of scales, but dominate hydrological responses over a narrower spectrum. Of the anthropogenic variables shown in Figure 2.5 (bottom), for example,

- *tillage practice*, i.e. conventional vs conservation vs minimum tillage practices, or ripping, terracing and contour banking, or
- *cropping practice*, i.e. crop rotation patterns, plant dates, plant densities, or
- *farm scale management*, which would include individual borehole abstractions or local irrigation from farm dams up to ~ 10^5 m^3 capacity

might have major impacts at local hydrological scale, but hardly a major one on larger river basins. Thereagainst,

- *land use and cover type*, which would include extensive natural grazing, urban areas, cropland and commercial plantation afforestation, as well as
- *water engineered management*, into which category major reservoirs (i.e. > 10^8 m^3), regional scale irrigation, water diversions and inter-basin transfers fall; and the
- *status of socio-economic development*, in which distinctions would be made between developed and lesser developed economies, or between predominantly commercial vs subsistence agriculture, would all, by themselves or in combination, be able to change natural hydrological regimes at the catchment scale.

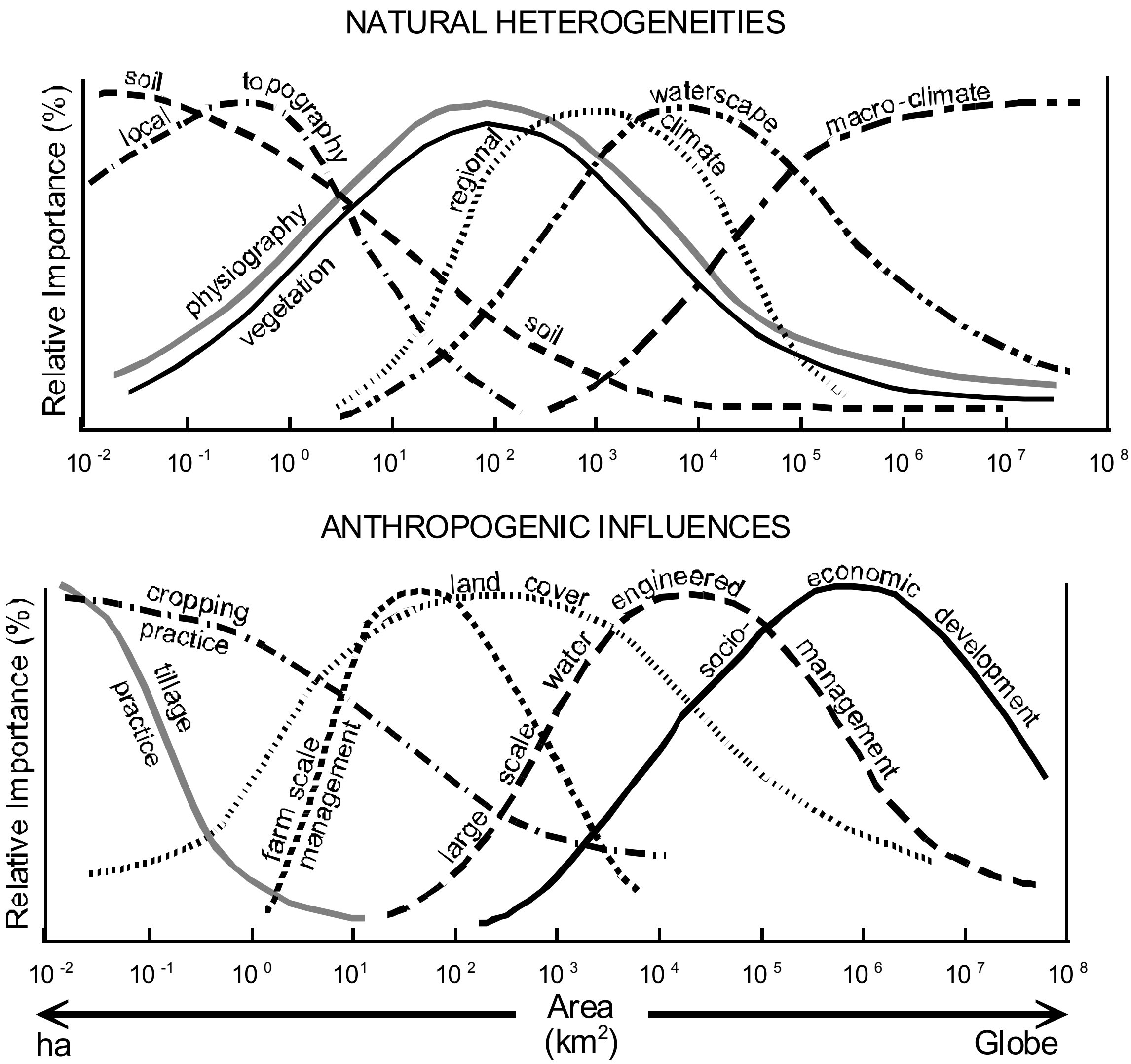


Figure 2.5 Natural heterogeneities (top) and anthropogenic influences (bottom) occur across a range of spatial scales, but dominate hydrological responses over a narrower spectrum

2.1.5 Intra - annual variabilities of hydrological responses are even higher than inter - annual ones[2]

Two examples using *ACRU* model simulations in the Thukela catchment in South Africa illustrate this premise.

In the first, Figure 2.6 shows CoV% of stormflows in Subcatchment 3 in the Nadi area (MAP = 552 mm) to be 100% - 250% in the wet summer months October to April, and increasing to 250% - 500% in the drier months from May to September, during which monthly total stormflows are even less reliable than in summer. Similarly, month-by-month CoV% of baseflows vary from ~160% to > 300% (depending on land use). For both these two runoff components the monthly CoV% are usually markedly higher than the annual values.

The second example, from two key locations in the Thukela Catchment, similarly displays coefficients of variability of both "wet" and "dry" months (October-March; April-September, respectively) to be considerably higher than annual values - in this case for recharge of water percolated through the soil profile into the vadose zone which separates the surface and groundwater stores. At Cathedral Peak, which at MAP 1 200 mm is in the high runoff producing zone of the Thukela, both "wet" and (especially) "dry" month CoVs are 2-7 times higher than the CoV of total annual recharge, while in the more semi-arid Keate's Drift area, where CoV of annual recharge is 2½ times that of Cathedral Peak's, "wet" and "dry" month CoVs are, once more, up to 3 times (200-600%) that of an already high CoV of recharge at ~200% (Table 2.1).

Table 2.1 Coefficients of variation (%) of recharge into the vadose zone at different times of the year at a high rainfall (Cathedral Peak; MAP ~1 200 mm) and lower rainfall (Keate's Drift; MAP ~650 mm) location in the Thukela Catchment (Schulze, 2003)

Period	Coefficients of Variation (%)	
	Cathedral Peak	Keate's Drift
Inter-Annual	80	207
Wet months	~200	~200-400
Dry months	~400-600	~300-600

This phenomenon of excessively high coefficients of variation of within-year periods further exacerbates management of both surface and groundwater.

2.1.6 Different components of the hydrological system differ markedly in their responses to rainfall variability[2]

The amplification by the natural hydrological system of any variation and/or change in climate has already been alluded to. This amplification is not of the same order for all hydrological responses, however, but rather it is graded. The case of the severe 1982/83 El Niño over southern Africa serves to illustrate this (Figure 2.7).

- Rainfall during this El Niño season was, on average, 60-75% of median rainfalls (Figure 2.7, top).
- Runoff, i.e. stormflow plus baseflow as generated with the daily time step physical-conceptual *ACRU* model, on the other hand, was generally only 20-40% of the median (Figure 2.7, middle). Furthermore, its responses were spatially much more variable than those of rainfall because runoff responds not only to broad rainfall trends, but also to characteristics of individual rainfall events (magnitude, intensity, persistencies of raindays etc) as well as to antecedent catchment conditions.

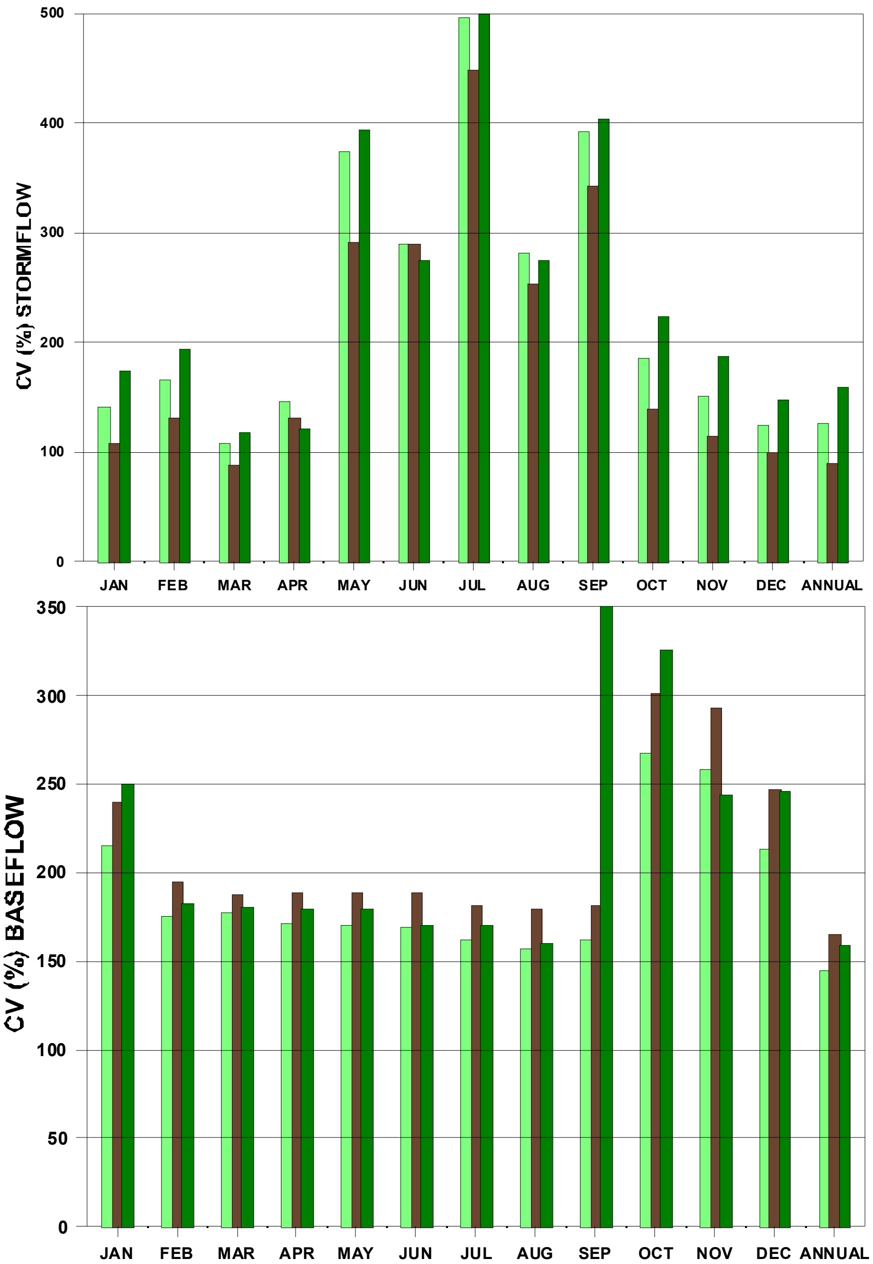


Figure 2.6 Month-by-month and annual coefficients of variation (%) of stormflows and baseflows in Subcatchment 3 of the Nadi catchment for three land uses (Schulze *et al*., 1997)

- Recharge to the Groundwater Zone during the 1982/83 season was even less, at < 20% of the median (Figure 2.7, bottom) since recharge takes place following either individual large events or sustained rainfalls.

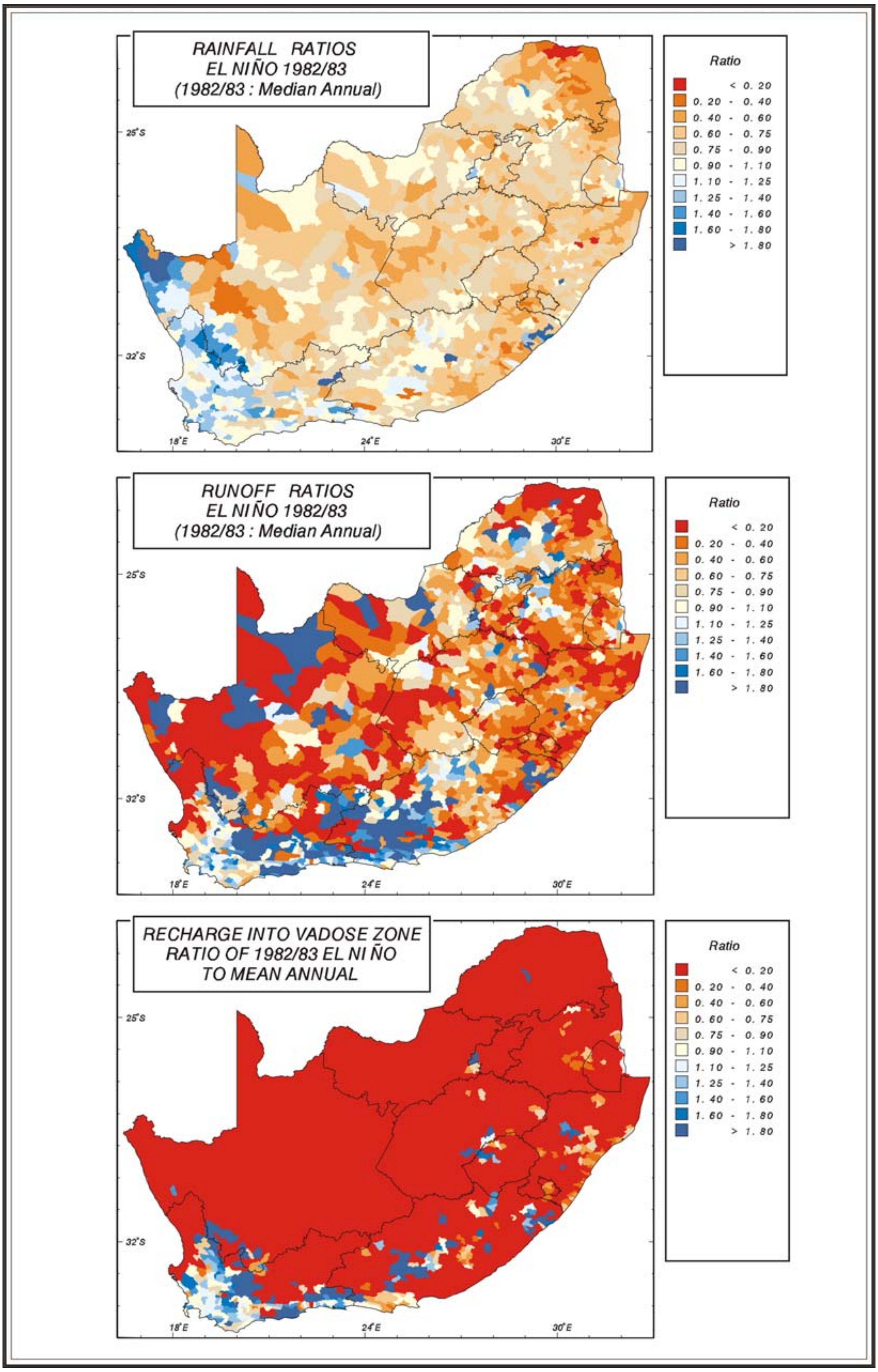


Figure 2.7 Different responses by components of the natural hydrological system to change in rainfall: Example from the 1982/83 El Niño in southern Africa (after Schulze, 1997b)

This grading of hydrological responses is important to water resources planners, who rely either on surface waters or on groundwater, which respond differently to changes in climate.

2.1.7 Streamflow variability is high in individual external subcatchments, but in a river system becomes attenuated in internal and mainstream subcatchments[2]

The higher the stream order within a river system, the less variable streamflows generally become because flow contributions accumulate from different parts of catchment which do not generate runoff identically nor at the same time, and because flows are attenuated downstream. This premise is well illustrated by the Thukela catchment with its 113 interlinked subcatchments, with Figure 2.8 showing clearly the reduction in coefficients of variability along major tributaries and the mainstem, i.e. the "internal" subcatchments, when compared to the CoV(%) of "external" subcatchments.

While this premise is important to bear in mind when major reservoir projects are planned, it needs to be stressed that rural communities in South Africa have NOT generally settled close to mainstem rivers with their more assured supply of water. Rather, they tend to live closer to watershed boundaries near lower order streams with their more variable, often ephemeral, flow patterns. This makes rural community water supplies for domestic and irrigation purposes from surface water sources a difficult, costly and challenging task.

2.1.8 Land use change by intensification or extensification of biomass often increases flow variability because it changes the partitioning of rainfall into stormflow and baseflow components[2]

An example of intensification of land use would be the conversion of grassland (comparatively low above ground biomass; therefore low interception and transpiration; shallow roots; seasonal growth) to plantation forest such as *Eucalyptus grandis* (high biomass and hence interception and transpiration; deep roots; evergreen). On the other hand, extensification would include deforestation of natural woodlands or overgrazing (reduction of biomass and transpiration; bare soil exposure and soil sealing). In the case of intensification, interception losses are increased, as is infiltrability and the active root depth. Intensification in crops can also imply use of conservation structures. Stormflow generation is therefore reduced, becomes more intermittent and is a feature of major events only. Extensification, thereagainst, enhances stormflow generation, but baseflow generation becomes more intermittent.

These changes in flow variability have been illustrated previously in Figure 2.6 in which intensification of grassland in "good" hydrological condition to *E. grandis* plantations generally increases the CoV% of stormflows while extensification to degraded grassland increases the CoV% of baseflows in all months of the year.

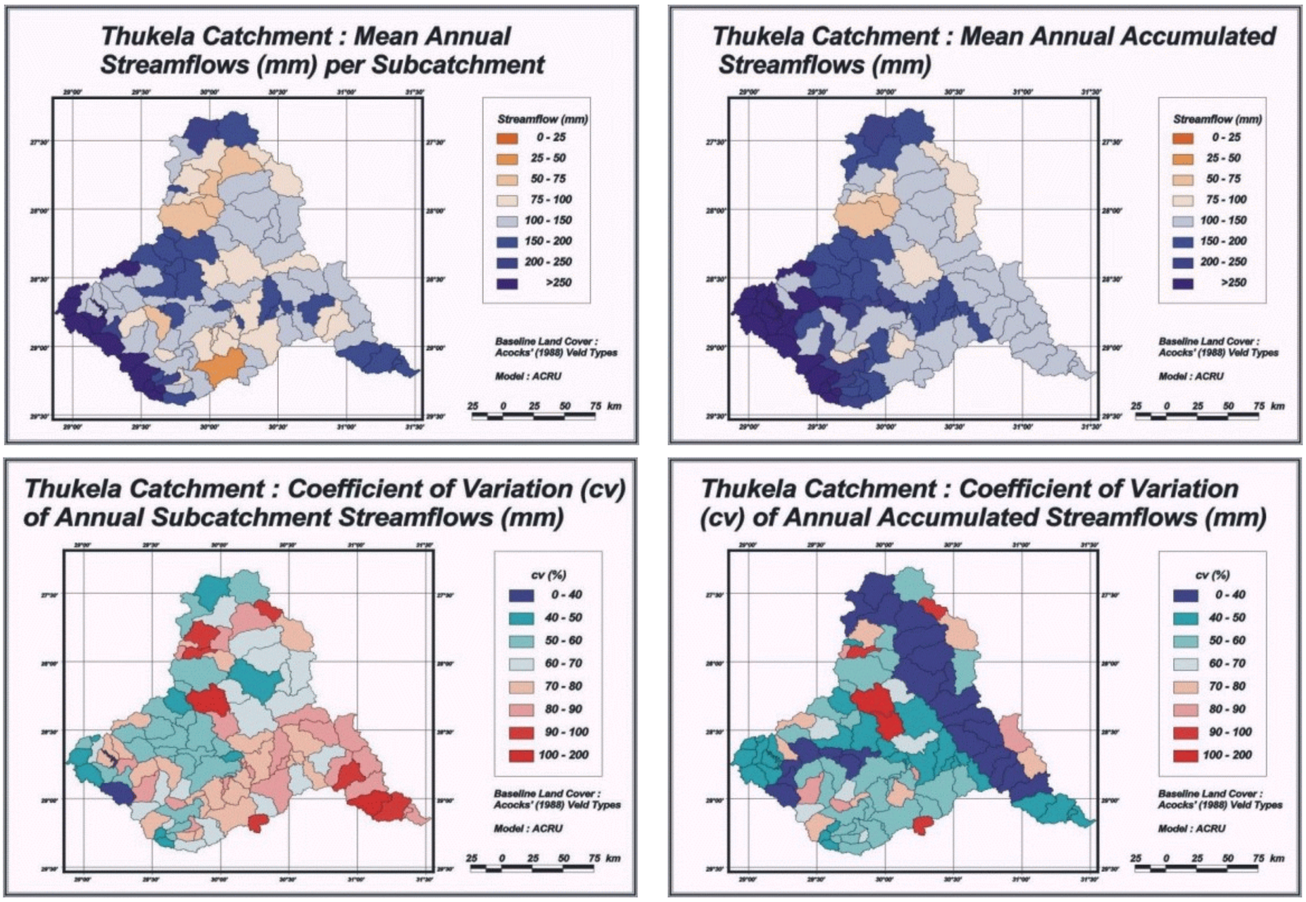


Figure 2.8 Spatial variation of streamflows (after Schulze and Dlamini, 2002)

2.1.9 Degradation of the landscape can amplify further any hydrological responses, especially higher order responses[2]

By higher order hydrological responses, for example, changes in water quality components such as sediment yield are implied. As an illustration of this premise, Figure 2.9 shows that the degradation from well managed grassveld in good hydrological condition (> 75% cover, > 40% litter layer of dead leaves) to veld in poor condition (< 50% canopy cover, only 20% litter, reductions in infiltrability and above-ground biomass) would generally increase stormflows over South Africa by 1.5 to 2.5 times. The corresponding sediment yields, however, are simulated to increase by a factor of 5 to 10 (Schulze, 2001).

With large tracts of South Africa, Swaziland and Lesotho in various stages/degrees of veld degradation, this significant further amplification by hydrological responses should be of major concern to veld conservationists and reservoir design engineers alike, reducing not only fertile topsoil and the full supply capacity of reservoirs over time, but also adding to the cost of water treatment. With the advent of higher convective activity which GCMs are predicting for a future climate, the problem of sediment yield is likely to be further exacerbated.

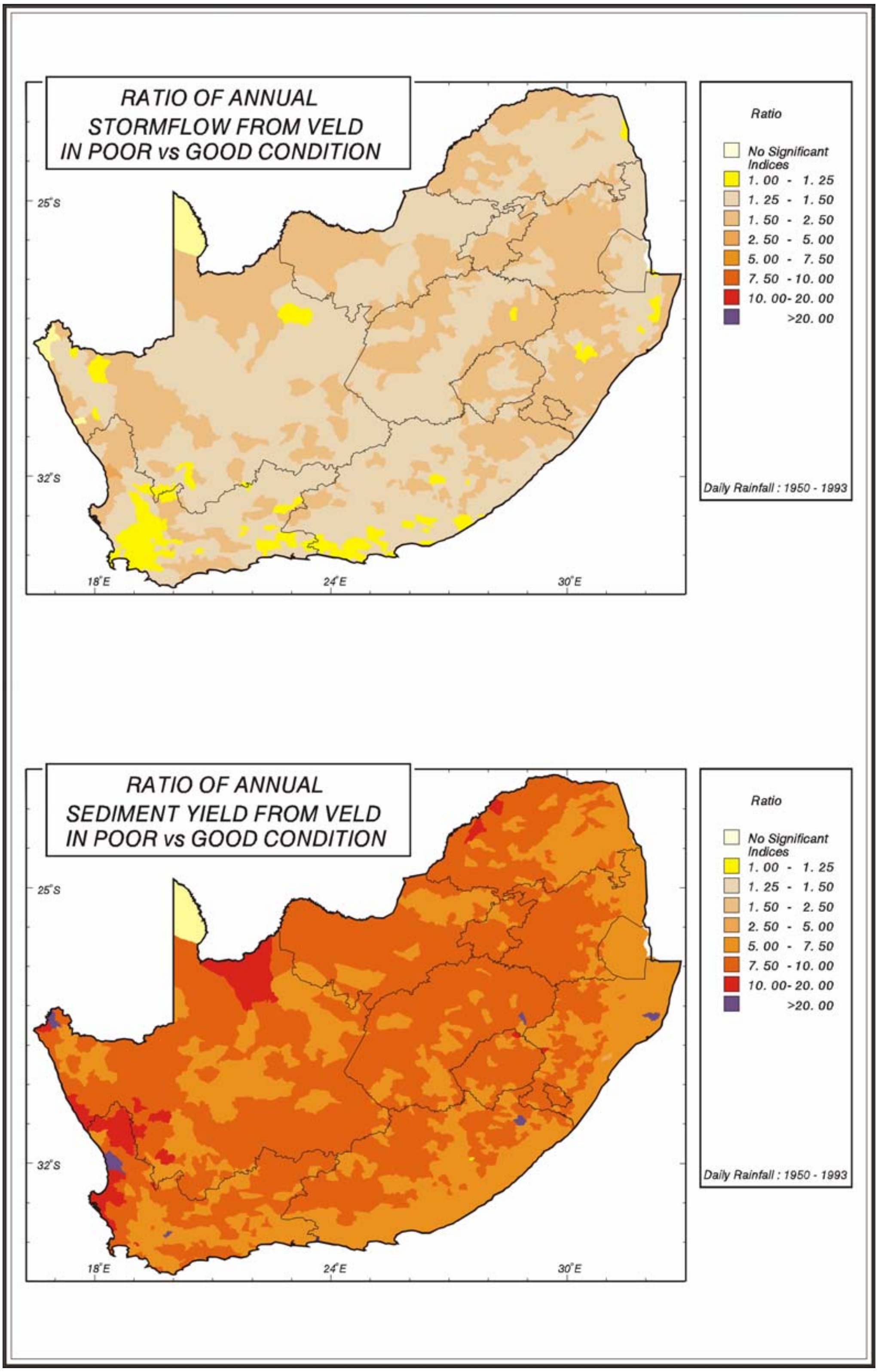


Figure 2.9 Amplification of stormflows and sediment yields through degradation of the landscape from grassveld in well managed to poorly managed condition (Schulze, 2001)

2.1.10 Persistencies exacerbate variability[2]

Observation of historical data series has demonstrated that the sequencing of wet and dry years is not distributed evenly, but rather that extended dry and wet periods can occur in some regions. This is illustrated in Figure 2.10 for annual rainfall averaged over the entire South Africa for the period 1922-1999 and in Figure 2.11 for a more local region *viz.* the Kruger National Park. The drought experienced in the West African Sahel region during the 1970s and the 1980s is another illustrative example in this regard.

In addition to short cycles of individual above or below rainfall seasons Figure 2.11 also displays

- ***persistencies in seasonal rainfalls***; with sequences of consecutive above average seasons (e.g. 1916/17-1922/3), 1973/4-1977/8) or below average rainfalls (e.g. 1925/6-1928/9, 1961/2-1965/6),
- ***longer periods of dominantly above or below average rainfall*** where blocks of 7-11 seasons are largely above or below average, but are interspersed with occasional seasons of opposite sign (e.g. the 1914/15-1924/5 wet period with only 2 below average years, or the 1961/2-1969/70 dry period, again with only 2 above average years) and
- ***apparent multi-decadal cycles*** of which the 1914-25 flood producing cycle is possibly, but still with much uncertainty, repeating itself at the present time.

The variabilities of streamflows in the Thukela catchment, both for individual subcatchments and accumulated flows, have already been illustrated in Figure 2.8. In order to evaluate further aspects of flow variability, time series of flows and their components were produced by Schulze and Dlamini (2002) at Keate's Drift with the daily time step *ACRU* model (Schulze, 1995). Immediately noticeable in perusal of the sequence of annual flows in Figure 2.12 (top) is not only the high inter-annual fluctuation of flows, but also the high frequency of consecutive (persistent) years of high or low flows. Implications of this are the need for storage facilities to be excessively large to cope with abstractions when droughts of several years' duration occur. This need is not always fulfilled in rural communities, which frequently depend on small dams with capacities well below 1 x MAR, and which can run dry well before major droughts have been broken. Further implications of excessive highs and lows, is the need for sophisticated disaster management to be in place.

Flow variability is even more pronounced from year to year during the critical low flow months June, July and August (Figure 2.12, middle), re-emphasising the need for sufficient water storage, especially as borehole yields may be reduced during dry months, but also focusing on the needs for strong policies in regard to the equitable allocation of water to competing users, and on sound pro-active drought management. The example of low flow variability stresses the importance of accurate seasonal streamflow forecasts as an operational tool for water poor areas.

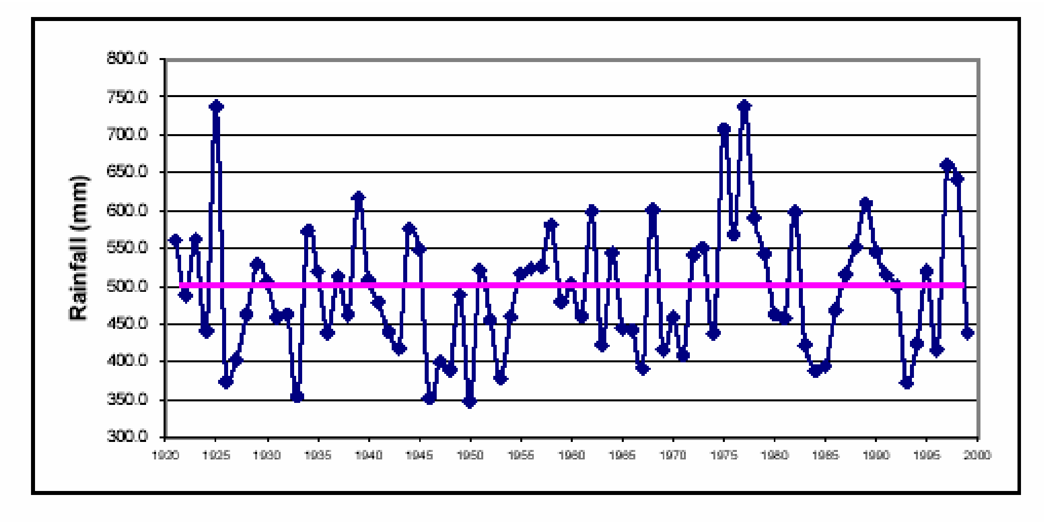


Figure 2.10 Annual averages of rainfall over South Africa (1922-1999) illustrating the frequent persistence of a series of wet or dry years (Source: South African Weather Service, 2000)

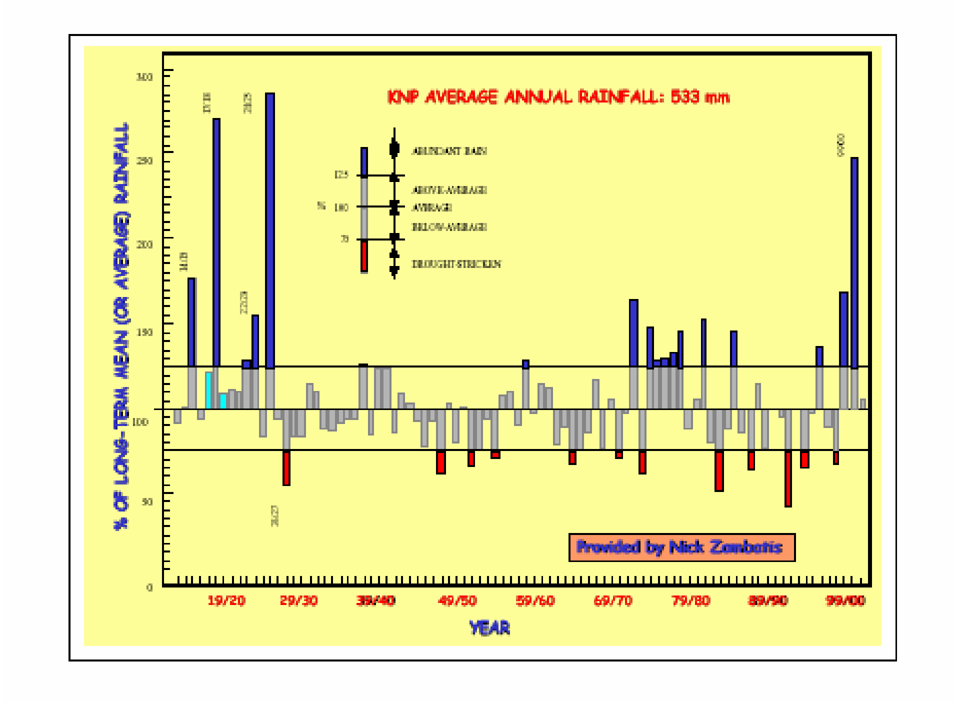


Figure 2.11 Annual variability of averaged rainfall over the KNP from 1912/13 to 2000/01 (after Venter, 2003)

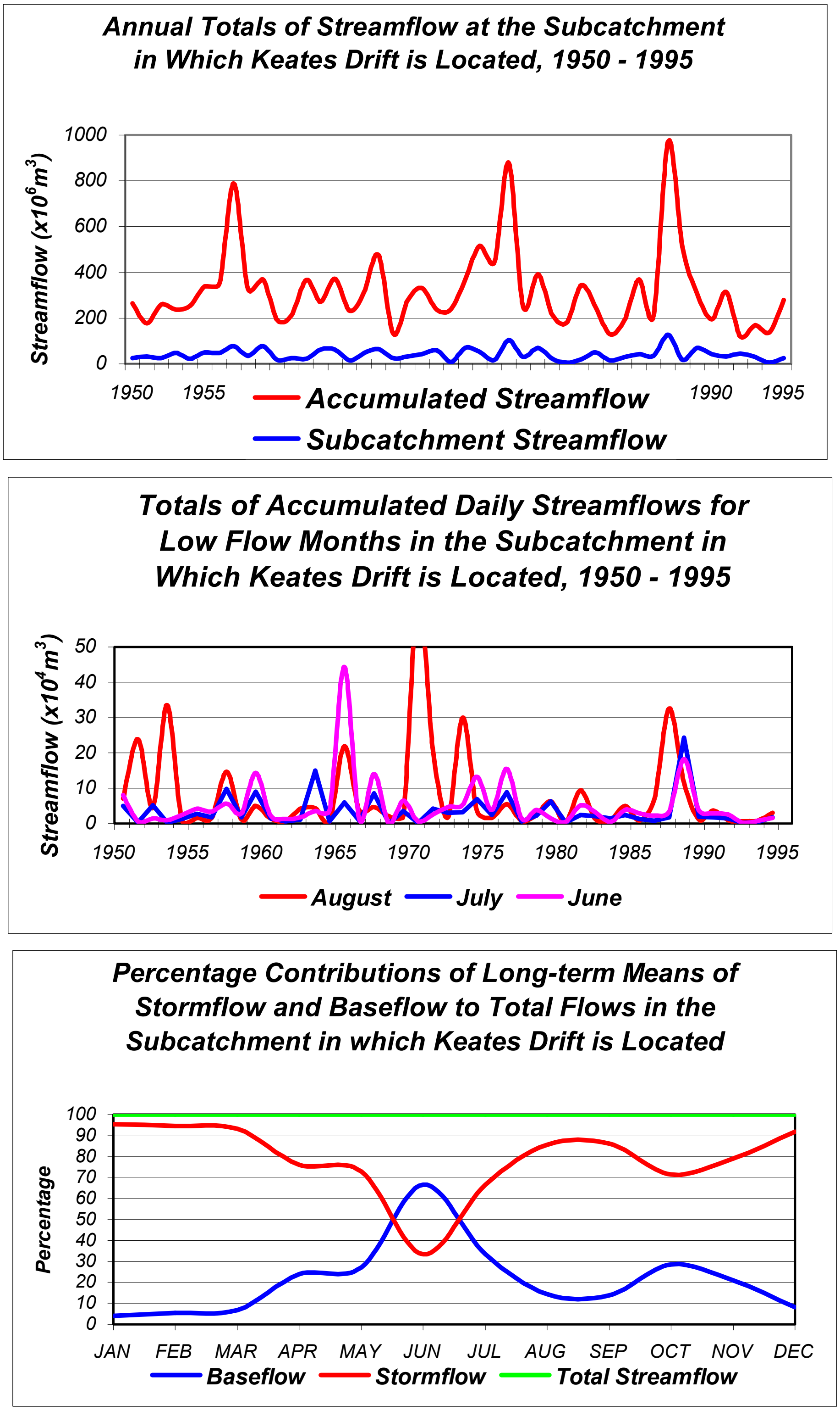


Figure 2.12 Temporal variations in streamflows at Keate's Drift (after Schulze and Dlamini, 2002)

Figure 2.12 (bottom) on the relative contributions of stormflows and baseflows to total streamflows shows stormflows to dominate for most of the year, with baseflows the major source of water only in the low flow months. Not only is the chemical water quality then likely to be lower but, coupled with the high variability of low flows, communities may need to choose different sources of water in different seasons, with implications on distances needed to travel to obtain daily household water supplies.

2.1.11 The hydrological cycle, resilience and thresholds[1]

Experience has shown that the hydrological cycle has a certain resilience, i.e. it is able to accommodate only a certain level of external forcing, such as a reduction in precipitation. If, however, the forcing is too strong, or is maintained for too long, river flows may drop suddenly and sharply, with the associated consequences for the different users of water (the ecosystems and Man). For example, Figure 2.13 illustrates this concept, as a prolonged decrease in precipitation results in a sharp reduction in river flow for the Bani River, a major tributary to the Niger River in Mali.

2.2 WATER IS A LOCAL ISSUE[1]

Although figures show that at the global level the increase of water demands and uses appears as being the determinant driver in what can be considered as a looming crisis, it must be pointed out that the relationship of humans with water is largely defined at the local level, with water being considered either as a resource or as an ecosystem. Global and even national indicators hide the obvious fact that for all beings, scarce water means survival and no water at all means death within a few days. In many stressed environments, the resource component in the demand/supply balance may, indeed, become the key issue if the resource is modified in total amount or in its temporal or spatial distribution by, for example, changes to mean climates and climatic variability.

2.3 CLIMATE AND ECOSYSTEMS[1]

The concept of freshwater should not be reduced to that of a mineral flowing through channels, canals and pipes. Freshwater is an essential driver of terrestrial and aquatic ecosystems. Any state of equilibrium in the distribution of terrestrial ecosystems results from a balance between climatic conditions and the capacity for resilience of the systems to variations in those climatic conditions. Any change in the variability of climate, or any trend in any one of its components, may lead to latitudinal and altitudinal shifts in the distribution of terrestrial ecosystems (e.g. rainforests, savannas, steppes). In a given watershed (also termed catchment or basin), these changes might have tangible effects on the water budget and thus on the availability of water resources.

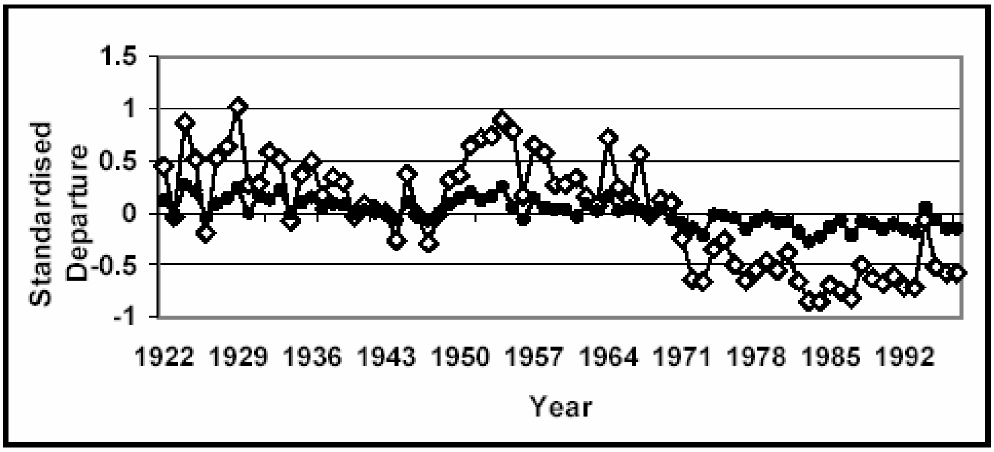


Figure 2.13 Bani River at Douna (Mali). Compared evolution of precipitation (black circles) and river flow (open diamonds) for the period 1922 to 1997. Units: Standardised departure from the inter-annual mean (Source: Mahé *et al.*, 2000)

Freshwater ecosystems (such as ponds, lakes, wetlands and rivers channels) are essential components of the environment. They provide support for the existence of aquatic and terrestrial wildlife, environmental goods (e.g. water, foods) and services (such as flood attenuation, depletion of organic pollution). In many regions fish are a key element in the social and economic organisation of human communities and are the first source of proteins, and sometimes the only one, especially for the poor. Further issues on the importance of the environment in water resources, considering only present climatic conditions and not any further repercussions of enhanced warming or variability, are expanded upon in Box 2.1.

2.4 WATER AND HEALTH[1]

Unfortunately, water is also associated with specific diseases. There are several ways in which water is involved in transmission of disease:

- *Water-borne diseases* result from the contamination of water by human or animal faeces, or by urine infected by pathogenic viruses or bacteria, in which case the
- disease is transmitted directly when the water is drunk or used in the preparation of food.
- *Water-washed diseases* are those resulting from inadequate personal hygiene because of scarcity or inaccessibility of water. These include many water-borne diseases as well as typhus.
- *Water-based diseases* are those arising from parasites that use an intermediate host that lives in or near water (e.g. guinea worm).
- *Water-related diseases* are diseases borne by insect vectors, which have habitats in or near water (e.g. malaria).
- *Water-dispersed diseases* are infections whose agents proliferate in fresh water and enter the human body through the respiratory tract (e.g. Legionella).

In many of these cases, variability of water availability is a major trigger to disease manifestation and climate change could exacerbate the incidence of disease outbreaks.

Box 2.1 The importance of the environment in water resources

With a water crisis facing many countries, it seems an immense task just to manage water so that there is enough for domestic supply, agricultural and industrial uses. Thus, providing water to other users, such as the 'environment' is often given a low priority. Indeed, the situation is often presented as a conflict of competing demand, as though it was a matter of choice between water for people and water for wildlife. However, since the UNCED Conference in Rio in 1992, it has become increasingly recognised that the 'environment' means far more than just wildlife, although the need to conserve biodiversity is widely accepted. Functioning ecosystems perform vital functions such as flood reduction, groundwater recharge and low flow augmentation, and important products, such as fish, pastureland, reeds, medicines and timber (Acreman, 1998). Thus for the millions of people worldwide, particularly the rural poor who depend directly on natural resources or benefit from ecosystems, providing water for the environment and for people are one and the same (Acreman, 2001).

The Dublin Conference in 1992 (a preparatory meeting for UNCED) concluded that 'since water sustains all life, effective management of water resources demands a holistic approach, linking social and economic development with protection of natural ecosystems'. For example, upstream ecosystems need to be conserved if their vital role in regulating the hydrological cycle is to be maintained. Well-managed headwater grasslands and forests reduce runoff during wet periods, increase infiltration to the soil and aquifers and reduce soil erosion. Downstream ecosystems provide valuable resources, such as fish nurseries, floodplain forests or pasture, but these must be provided with freshwater and seen as a legitimate water user. At the UNCED Conference itself, it was agreed that '*in developing and using water resources priority has to be given to the satisfaction of basic needs and the safeguarding of ecosystems'* (Agenda 21, Chapter 18, 18.8). Thus whilst people need access to water directly to drink, irrigate crops or supply industry, providing water to the environment means using water indirectly for people. The declaration from the Second World Water Forum in The Hague in 2000 highlighted the need to ensure the integrity of ecosystems through sustainable water resources management. South Africa is one of the countries which have taken a lead in implementing this concept. Principle 9 of the new (1998) National Water Act of South Africa states that 'the quantity, quality and reliability of water required to maintain the ecological functions on which humans depend shall be reserved so that the human use of water does not individually or cumulatively compromise the long term sustainability of aquatic and associated ecosystems'. The 1996-2001 Fifth International Hydrology Programme of UNESCO included an Ecohydrology project which includes ecosystem management to improve water quality, particularly in the form of buffer strips to ameliorate the impacts of agricultural pollution. The World Commission on Dams (2000) recommended the release of environmental flows from dams to support downstream ecosystems and their dependent livelihoods.

2.5 CLIMATIC EXTREMES

2.5.1 What is the importance of climatic extremes?[4]

Extreme weather and climate events have received increased attention over the past decade, largely as a result of the exponentially-increasing losses that have been associated with them. Yearly economic losses from large events have increased tenfold between the 1950s and 1990s. These losses largely reflect an increase in the vulnerability of society as a whole to extreme events (Kunkel *et al*., 1999). In many cases this increased vulnerability has not been matched by an appropriate increase in adaptive capacity. Part of the observed upward trend in losses is linked o socio-economic factors, such as population growth, expansion into and population concentration in flood prone areas, increasing wealth, as well as land use and river channel changes. However, these factors alone cannot explain the observed growth in economic losses; part of the losses can be linked to climatic factors, such as more intense storms, floods and droughts.

The World Bank's Water Resources Sector Strategy quotes examples of impacts of climate variability on economic performance. The drought in Zimbabwe in the early 1990s was associated with an 11% decline in GDP; the floods of 2000 in Mozambique led to a 23% reduction in GDP, and a drought in Brazil in 2000 halved projected economic growth. The scale of these losses highlights the need for water planners and managers to have a better understanding of the mechanisms of climate variability and their relationships with hydrological extremes such as floods and droughts.

It is difficult to quantify the impacts of human activity on climatic extremes. Lack of long-term climate data suitable for analysis of extremes is the biggest obstacle to quantifying how extreme events have changed over the 20th century, either world-wide or on a regional basis (Easterling *et al*., 1999). However, recent changes in climate variability certainly seem to have adversely affected flood and drought hazards in several regions and this tendency is likely to continue.

2.5.2 Climatic extremes and the El Niño-Southern Oscillation[4]

There are a number of recognised large-scale climate phenomena, including the El Niño-Southern Oscillation (ENSO), North Atlantic Oscillation (NAO), Pacific Decadal Oscillation (PDO), and the Indian Ocean Dipole (IOD). At present, only climate forecasts based on the modelling of ENSO give any long-lead prediction accuracy. ENSO is one of the largest sources of natural variability in the global climate system. It is an anomalous large-scale ocean-atmosphere system associated with an irregular cycle of warming and cooling of sea surface temperatures (SSTs) in the tropical Pacific Ocean. The oceanic warming and cooling is accompanied by a 'see-saw' shift in surface air pressure between Asian and eastern Pacific regions (the 'Southern Oscillation').

The ENSO cycle has a time scale of from two to seven years and consists of three phases: El Niño (warm phase); La Niña (cold phase), and neutral periods. The long term behaviour of ENSO is poorly understood. A variety of indices are used to characterise ENSO because it affects so many components of the atmosphere-ocean climate system. The two main indices are the Southern Oscillation Index (SOI) and the Niño 3 index.

2.5.3 Where does the El Niño-Southern Oscillation fit into hydrological practice? An example from Australia[2]

The extremes of the ENSO cycle are partly responsible for large climate variability year-on-year in many countries and regions. In Southern Africa, Australia and Latin America, for example, ENSO is blamed for a large part of inter-annual climate variability.

Many studies have found reasonably strong relationships between streamflow variability and ENSO. From streamflow data for the Burnett River at Walla in Australia it was demonstrated that the chance of streamflows in September to December varied with July SOI phases. The consistently positive and rapidly rising July SOI phases relate to higher chances of reaching or exceeding specified streamflow amounts than the remaining SOI phases (Figure 2.14). Conversely, consistently negative July SOI phases relate to a lower chance of reaching or exceeding specified streamflows than the remaining SOI phases (Figure 2.14).

Whilst knowledge of streamflows is useful, it would be more beneficial to farmers if announced water allocations at particular times of the year could be forecasted accurately. For example, if there was an increased chance of above median streamflows, but there was no storage available to capture these extra streamflows, then such a forecast on streamflows could be misleading. Given that the SOI phase system shows quite good skill at forecasting streamflows, it was decided to assess if this could be translated to forecasting water allocations (Everingham *et al.*, 2003).

Likely allocation increases were computed by entering historical streamflow sequences for September to December into an irrigation allocation model. For each sequence of streamflows an allocation was produced as output from the allocation model.

It was found that the chance of certain announced allocations at the end of December varied with August SOI phases. Using the all years' data, there was a 50% chance that the allocation would exceed 60% at the end of December. If the August SOI phase was consistently negative, then the chance of exceeding 60% would be about 25%, or one in four. Conversely, Everingham *et al* (2003) found that the chance of exceeding 60% is much higher (approximately 75%) if the SOI phase for August was consistently positive (Figure 2.15).

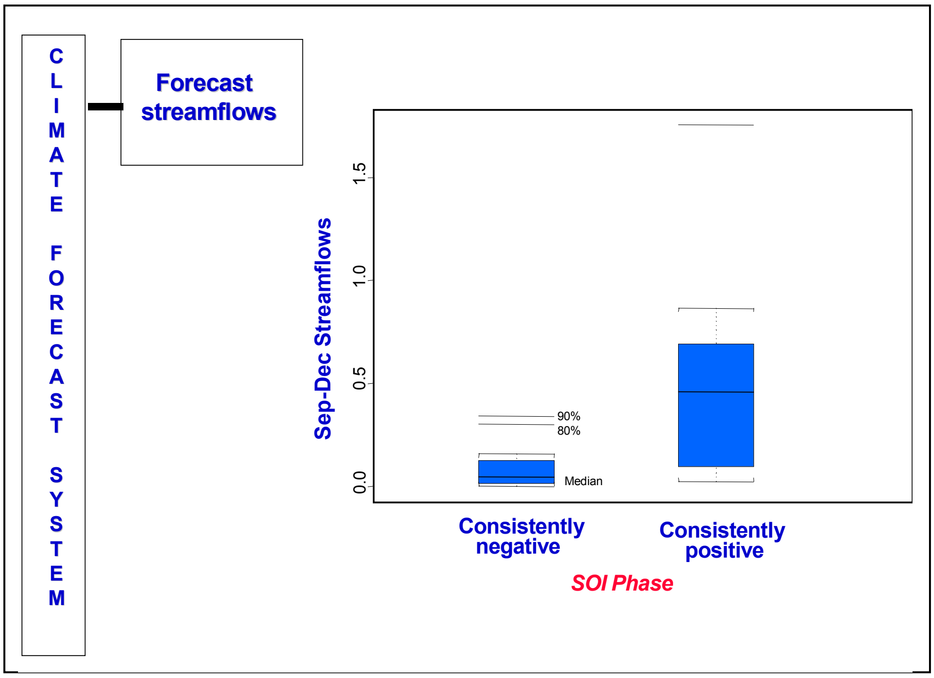


Figure 2.14 Targeted climate forecasts 1: Streamflows for September to December forecasted according to SOI phases in July (after Everingham *et al*., 2003)

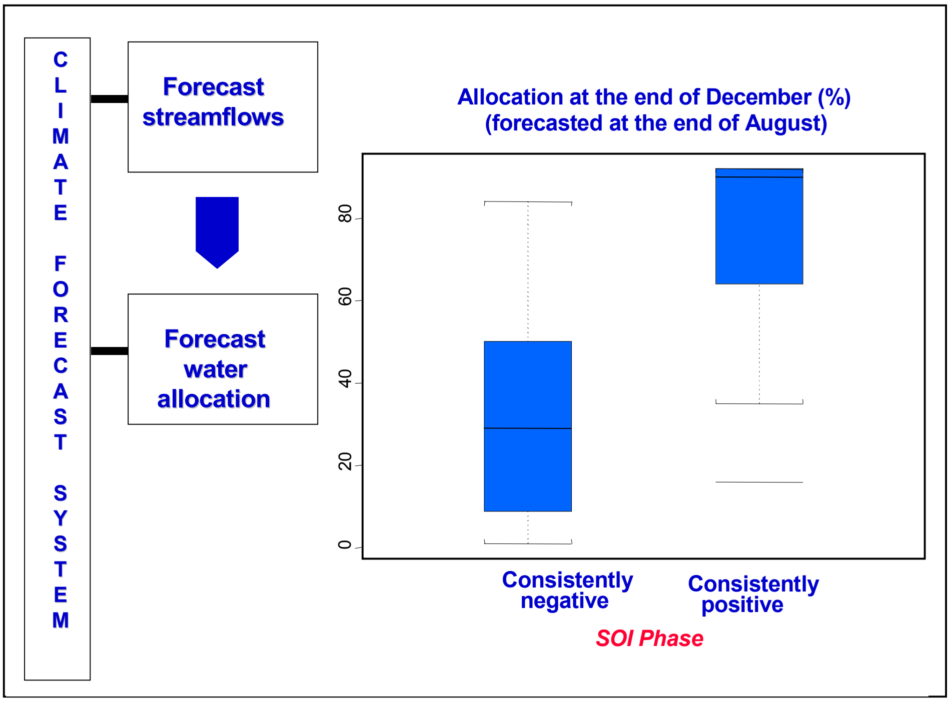


Figure 2.15 Targeted climate forecasts 2: Forecasted water allocations for the end of December from SOI phases in August (after Everingham *et al*., 2003)

In summary, the outlined approach is a novel way of providing farmers with more detail about likely announced allocations at the end of December for the current SOI phase with a lead-time of some four months. This information has previously not been available to farmers.

2.6 FLOODS

2.6.1 Why do floods matter?

2.6.1.1 They are natural phenomena[1]

For millennia, people have settled in floodplains in order to till fertile soils, use the flat terrain for settlements, have easy and safe access to water and to use the river for transport. Riverine floods are natural phenomena: they have always occurred and people have tried to benefit from them to whatever extent possible. However, in recent decades humans have become more exposed to the risk of floods.

2.6.1.2 There is now more exposure to floods[1]

Different pressures have combined to increase population densities in flood-prone areas, including shortage of land, which has caused encroachment into floodplains. In particular, the mushrooming of informal settlements in endangered zones and around mega-cities in developing countries has occurred as people migrate towards economically developed city centres. The hope of overcoming poverty drives poor people to migrate, frequently into places vulnerable to flooding and where effective flood protection is not assured. In fact, in many countries such places are left uninhabited on purpose, exactly because they are flood-prone.

As a consequence, riverine floods have affected large numbers of people in recent years – on average more than 100 million people per year. From 1990 to 1996 there were 6 major floods throughout the world in which the number of fatalities exceeded 1000 while there were 22 floods with losses exceeding $US 1 billion each. According to the Red Cross, floods in the period from 1971 to 1995 affected more than 1.5 billion people worldwide. This total includes 318 000 killed and over 81 million homeless (IFRC, 997).

2.6.1.3 Negative aspects of floods[1]

The impact of floods has increasingly detrimental and disruptive effects on, *inter alia*,

- human health (*e.g.* the increased spreading of diseases such as diarrhoea or leptospirosis in flooded areas)
- settlements and infrastructure
- coastal areas
- financial services (including insurance and reinsurance)

- transport
- water supply
- agriculture and
- ecosystems.

2.6.1.4 Positive aspects of floods[1]

Not all floods are bad, however. Floods are the life blood of many ecosystems, including the floodplains and deltas. When flooded periodically, these wetland ecosystems supply important products (e.g. arable land, fisheries, livestock grazing), functions (e.g. groundwater recharge, nutrient cycling) and attributes (e.g. biodiversity), which have contributed to the economic, social and environmental security of rural communities worldwide for many centuries. Floods are also very important for fish migration and sediment transport. Furthermore, it is becoming more widely recognised that reduction in the frequency and magnitude of flooding caused by dams alters the conditions to which ecosystems have adapted and may degrade the natural services that provide benefits to people. In response, the release of managed floods was recommended by the World Commission on Dams (2000) and agreed as best practice as part of dam management by the World Bank (Acreman, 2002).

2.6.2 What do we know from the past about floods?

2.6.2.1 Increases in flood disasters[1]

Berz (2001) examined inter-decadal variability of major flood disasters, where flood disasters are understood to be those where the ability of the region to help itself is distinctly overtaxed, and thereby making international or interregional assistance necessary. Based on the data for the period 1950 to 1998, Berz (2001) contended that the number of major flood disasters had grown considerably world-wide in the past decades (six cases in the 1950s, seven in the 1960s, eight in the 1970s, 18 in the 1980s, and 26 in the 1990s). The number of major flood disasters in the decade of the 1990s was higher than in the three decades from 1950 to 1979.

In the 1990s, there were over two dozen flood disasters worldwide in each of which either the material losses exceeded $US 1 billion, or the number of fatalities was higher than 1000, or both. In the most disastrous storm surge flood in Bangladesh, during two days in April 1991, 140 000 people lost their lives. The highest material losses, of the order of $US 30 and 26.5 billion respectively, were recorded in China in the 1996 and 1998 floods.

As far as the geographic distribution of the most disastrous floods is concerned, the majority of recent large floods have occurred in countries of Asia. However, few countries of the world are free of flood danger, as demonstrated by the unprecedented floods in 2002 in Central Europe. Even countries located in dry areas, such as Yemen, Egypt and Tunisia have not been flood-safe. It is counterintuitive, but true, that in dry areas more people die of floods than from lack of water, as the dryness is a normal state to which humans have adapted, while floods strike unprepared populations suddenly.

2.6.2.2 Consequences in developed vs developing countries[1]

Although water-related extremes strike developed and less developed countries alike, their consequences are largely different. In developed countries, the material flood losses continue to grow, while the number of fatalities decreases. Advanced flood preparedness systems can save lives - the fatality toll in developed countries is far less than in the less developed ones. For catastrophic floods in developing countries, material losses per single fatality can be as low as $US 21 000, while in developed countries they can be as high as $US 400 million.

2.6.2.3 On detection of changes in floods: Precipitation[1]

Precipitation is a critical component in causing floods, and the location, form, amount, and intensity of precipitation appears to be changing. During the 20th century precipitation has increased by between 0.5 and 1.0% per decade in many areas over much of the mid- and high latitudes of the Northern Hemisphere. In regions where the total precipitation has increased, there have been even more pronounced increases in heavy and extreme precipitation events. Moreover, increases in intense precipitation have been documented even in those regions where the total precipitation has decreased or remained constant. However, one has to be careful with generalisations: there are some regions which have shown decreases in precipitation and precipitation intensity.

2.6.2.4 On detection of changes in floods: Runoff[1]

Changes in runoff are generally more difficult to detect than changes in precipitation. Nonetheless, an increasing number of large floods has been observed, as well as increasing flood damages in several areas such as in the USA. Moreover, a change in the seasonality of floods has been detected. This is due, in part, to earlier flow maxima following milder winters, and to a more persistent El Niño state. However, it would be a gross over-simplification to state that floods have exhibited growing trends everywhere. Signals in some river flow data, which have been ascribed to global warming, have not been confirmed by research elsewhere. The time series of flood data reflect complex responses due to other, non-climatic factors such as changes in catchment land use or manipulation of water within the channel (e.g. dams, abstractions, canalisation), and behaviour of such time series is not necessarily in tune with expectations from global climate-related prognoses alone.

2.6.2.5 Increases in costs and damages[1]

The costs of extreme weather events have exhibited a rapid upward trend in recent decades and yearly economic losses from large events have increased ten-fold between the 1950s and 1990s. Part of the observed upward trend in weather disaster losses is linked to socio-economic factors, such as increases in population and wealth as well as settlements expanding in vulnerable areas. However, these factors alone cannot explain the observed growth in economic losses. A part of losses can be linked to climatic factors, such as the observed changes in precipitation.

An example of research which links rates of change in flood characteristics and socio-economic indicators is that by Pielke and Downton (2000) in the USA for the time period from 1932 to 1997. They found that the total annual flood damage, adjusted for inflation, has grown at an average rate of 2.92% per year. That is a stronger growth than that of population (+1.26%) and tangible wealth per capita (in inflation-adjusted dollars +1.85%).

2.7 DROUGHTS

2.7.1 Why do droughts matter?

2.7.1.1 What are droughts?[1]

A drought occurs because of a lack of available water. This can manifest itself either through a lack of precipitation *per se,* or from a lack of available soil moisture for crops, or reduction of surface flows below a critical threshold, or of the amount of water stored in reservoirs, or reduced levels of groundwater. The impact of drought on a region depends on the adaptive capacity of the humans or ecosystems to cope with the lack of available water in its various forms. Droughts cause severe crop losses not only in semi-arid regions, but also in well-watered countries such as the Netherlands or Bangladesh.

2.7.1.2 What are the consequences of droughts?[1]

Droughts have several direct and indirect consequences on human livelihoods. A direct consequence of drought is crop loss, which can, in turn, cause starvation among humans if alternative food sources are not available. Indirectly, water shortage contributes to the proliferation of diseases, as people lack water for basic hygiene. If a drought persists, people are often forced to migrate. This occurred in the Sahel region in the 1970s, where drought persisted for 7 years. Finally, drought can inhibit regional development by contributing to a cycle of poverty.

2.7.1.3 What increases vulnerability to droughts?[1]

Semi-arid to arid regions generally display a strong climate variability (temporal and spatial) and hence have to cope with extremely dry situations on a frequent basis. Future climate changes are expected to change the frequency, severity and geographical location of droughts. However, in addition to climate variability and climate change, socio-economic changes generally increase vulnerability of particular populations to drought. For example, socio-economic drivers such as population growth or increasing demand for water per capita or loss of traditional knowledge and practices to adapt to drought or urbanisation, can all contribute to an exacerbation of a region's vulnerability to drought.

2.7.2 What do we know from the past about droughts?

2.7.2.1 Droughts and the poor[1]

In the past, it has been the poor who have suffered most from droughts. This will only change if this group can build up adaptive capacity. Unfortunately, the poor are not in a position to influence the mitigation of anthropogenic climate change. It is worth noting that political factors often exacerbate the problem of adaptation. For example, political priorities do not always favour adaptation options such as demand side management. In addition, national self-sufficiency in food production is often a strong priority, requiring that water be subsidised and/or allocated for agricultural production. Finally, many water resources (surface and groundwater) are transboundary and give rise to the possibility of conflicts over water allocation and use.

2.7.2.2 Droughts and the better off[1]

Even in developed countries an extreme drought may cause considerable environmental, economic and social losses. It is estimated that the 1988 drought in the USA may have caused direct agricultural loss of $US 13 billion. The more recent 1998-1999 drought affected the eastern regions of the USA and the grain growing period in 1999 was the driest on record for four states.

2.7.2.3 Can droughts be caused by human activity?[1]

There is evidence that some droughts have been caused by human activities. An extreme example comes from the Aral Sea basin where, due to excessive water withdrawals from the tributaries Syr Darya and Amu Darya, the Aral Sea has shrunk dramatically. However, there has also been a more widespread loss of moisture: in the latter half of the 20th century there has been increased drying out of the land in summer in some areas, increasing the risk of drought.

3. CLIMATE CHANGE AND WATER RESOURCES

3.1 LOOKING INTO THE FUTURE: POINTS TO PONDER ON CLIMATE CHANGE AND WATER REOURCES, WITH EXAMPLES FROM SOUTH AFRICA

3.1.1 As a consequence of greenhouse gas forced warming, the natural hydrological system will experience major repercussions[2]

In its simplest form, the natural hydrological system may be represented by the hydrological equation

$$Q = P - E + \Delta S$$

where Q equals streamflows, P is precipitation, E represents evaporation, made up of transpiration (Et), evaporation from the soil surface (Es) and free water evaporation (Ew) from intercepted water and that from open water surfaces (lakes, dams, river channels), while Δ S constitutes the changes in storage of soil and groundwater (Figure 3.1).

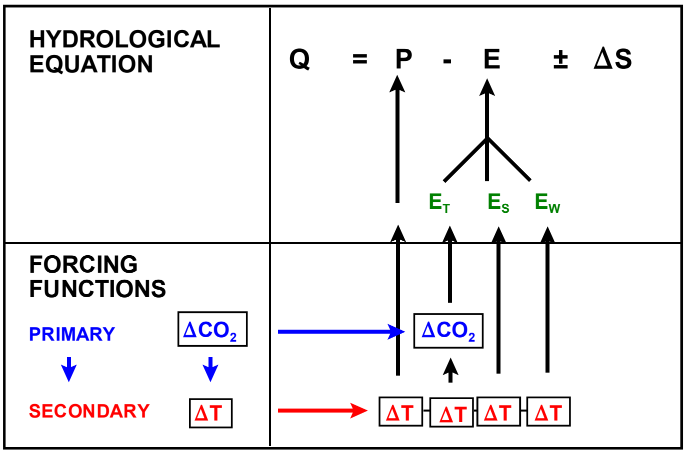


Figure 3.1 Greenhouse gas forced warming and the natural hydrological system (Schulze, 1997b)

In the hydrological equation above, the primary forcing function, ΔCO_2, alters Et directly, whilst the secondary forcing function, the Δ T, enhances both Es and Ew and simultaneously, through changes in atmospheric pressure belts, alters precipitation patterns and consequently, Δ S (Figure 3.1). These changes are elaborated on below from an hydrological perspective.

3.1.2 By itself, a change in atmospheric CO_2 concentrations can have important hydrological repercussions[2]

Increased atmospheric CO_2 concentrations, through changes in stomatal resistance, suppress maximum and thus actual transpiration at rates which vary between C3 plants (e.g. wheat) and C4 plants (e.g. maize, sugarcane), as well as the plants' biomass and the level of soil moisture content. These feedback processes, illustrated for maximum transpiration conditions in Figure 3.2, can reduce vegetative water losses significantly, depending on the ambient climatic status, and are represented in the daily timestep *ACRU* agrohydrological modelling system (Schulze, 1995) for both dryland and irrigated conditions.

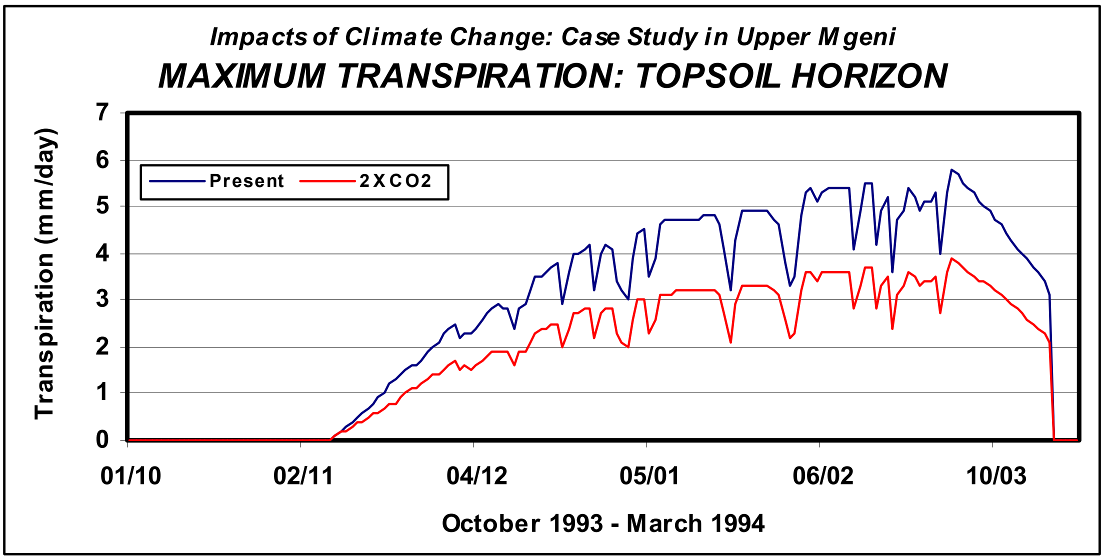


Figure 3.2 Example of transpiration feedback for C4 plants for a 2 x CO_2 equivalent climate change scenario superimposed on the upper Mgeni catchment's present climate for 1993 – 1994

Changes in atmospheric CO_2 concentrations will also result in changes to the carbon:nitrogen (C:N) ratios of the soil. For an effective doubling of atmospheric CO_2 concentrations the C:N changes over southern Africa are depicted in Figure 3.3. C:N ratios change the quality of forage to livestock, hence grazing patterns and the potential for geographical shifts in degraded areas, with potential consequences to stormflows and sediment yield as illustrated in Figure 2.8.

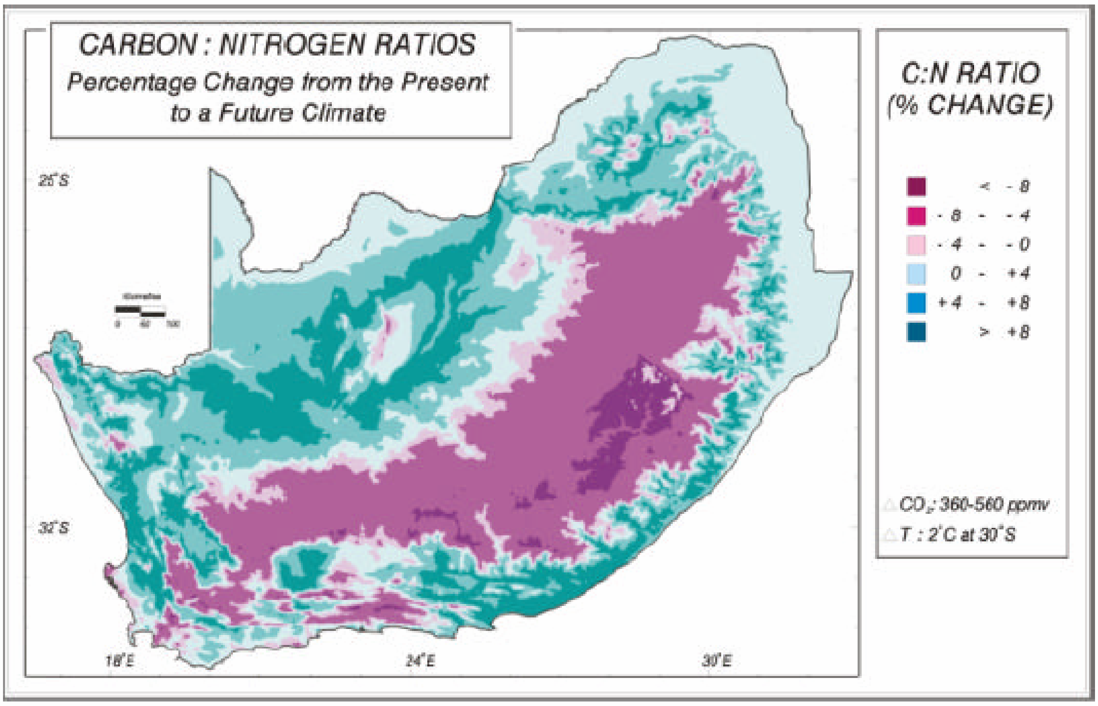


Figure 3.3 Changes in the C:N ratios of the soil over southern Africa (after Kunz *et al*., 1995)

3.1.3 By itself, a change in temperature regime can have important hydrological repercussions[2]

Temperature change, projected by GCMs such as the HadCM2 to increase over South Africa by between 1.5 - 3.5°C for an effective doubling of atmospheric CO_2 concentrations, will have direct and indirect bearing on hydrology and water resources through changes, for example, in

- ***potential evaporation*** (cf. Schulze and Perks, 2000)
  - from dams or
  - as an atmospheric demand on the soil/vegetation complex

  and hence
- ***soil moisture*** (cf. Schulze and Perks, 2000) and consequently
  - vegetation/crop water use
  - onset of plant stress and
  - runoff potential

  and, therefore,
- ***total*** ("actual") ***evaporation*** from the soil/vegetation complex; furthermore,
- ***dryland agricultural practices***, including
  - changes in the beginning and end of growing periods, as illustrated in Figure 3.4 by the dynamic temperature driven biomass change option now built into the
  - tillage practices
  - all with their alterations in hydrological response

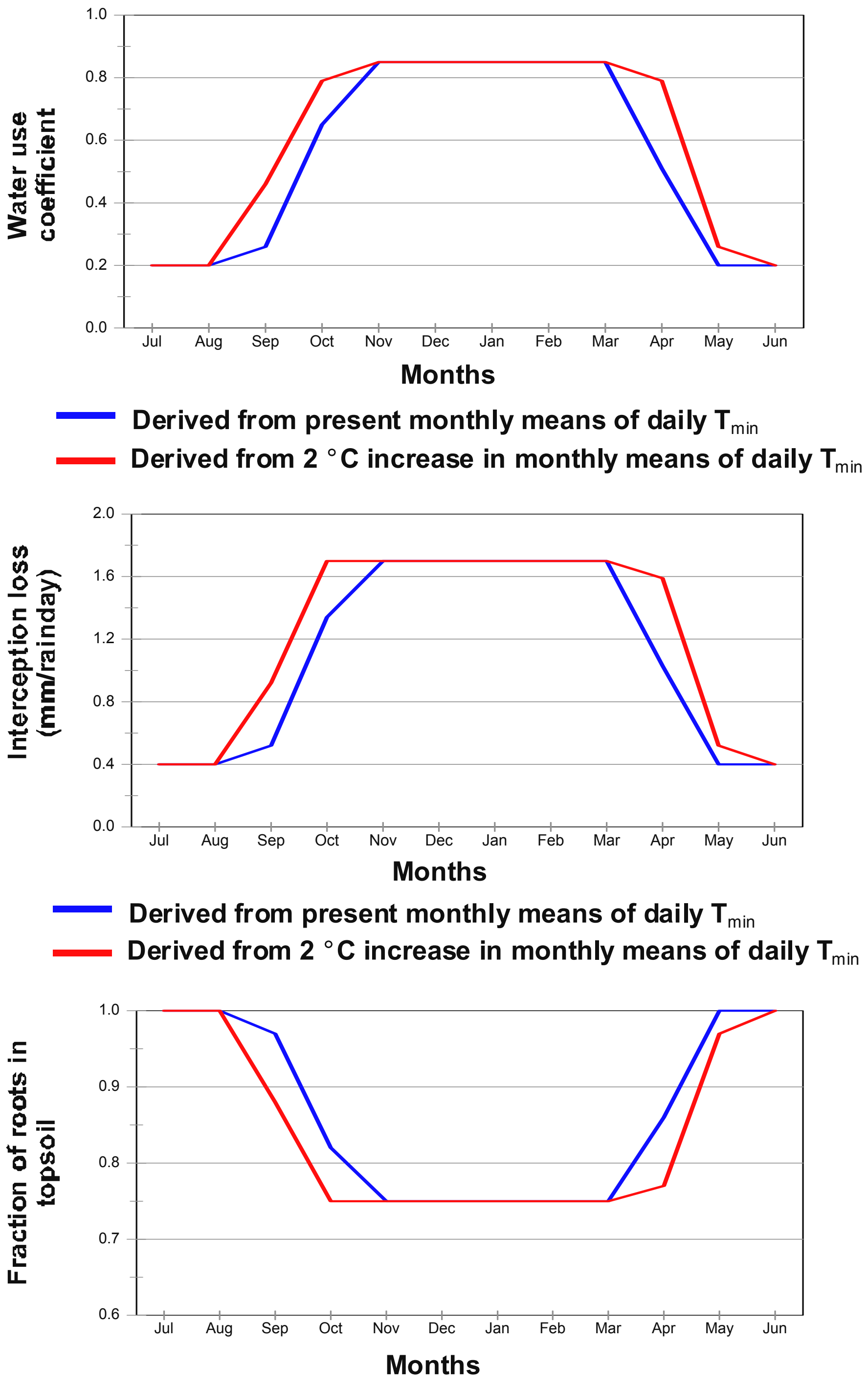


Figure 3.4 Example of dynamic changes in hydrologically related biomass indicators for a 2°C increase in temperature in the southern Free State province (Schulze and Perks, 2000)

irrigation practices, with different

- crops and crop water demands
- yield increments per mm irrigation and water use efficiencies, as well as enforced changes to
- modes of scheduling,

all of which are likely to be exacerbated by increased

- ***heat wave episodes*** and associated
- ***droughts***, in regard to their
  - frequencies
  - severity
  - duration and
  - spatial extent.

3.1.4 By themselves, changes in rainfall patterns and attributes will have wide ranging hydrological repercussions[2]

These changes will include possible

- ***changes in global patterns*** such as
  - ENSO events, with Timmerman *et al*. (1999), projecting increases in drier El Niño season frequencies from 24% to 34%, wetter La Niña phases to increase from 25% to 31% while neutral phase seasons will decrease from 51% for present climatic conditions to only 35% for the IPCC's IS92a climate change scenarios, and
  - sea surface temperatures, with possible (but not yet confirmed) increases in, and southward movement of, tropical cyclone activity around southern Africa
- ***changes in total magnitudes of, and seasonal changes in, rainfall***, with repercussions in
  - water demand and supply patterns
  - reservoir sizing and operations or
  - environmental flow requirements
- ***changes in individual event characteristics***, such as
  - increases in convectivity, which could result in
    - shorter hydrographs with higher peak discharges and
    - higher sediment yields
  - reductions in the number of raindays, which would affect
    - antecedent soil moisture conditions
    - runoff generation
    - sequences of wet/wet, wet/dry, dry/wet and dry/dry days
    - irrigation water demand and modes of scheduling and
    - recharge to groundwater

  or

  - increases in rainfall magnitude per rainfall event, with impacts similar to those above

  as well as

- ***changes in extreme events***, including the possibility of
  - simultaneously more flood events and droughts, because small changes in means would change frequency distributions significantly and result in higher probabilities of extremes (Figure 3.5), which would alter
    - reservoir sizing and
    - other water security strategies

  and
  - shifts in flood frequencies (e.g. a 1:50 year event becoming a 1:20 year event), implying possible changes in
    - hydrological design (e.g. spillways) and
    - disaster management preparation.

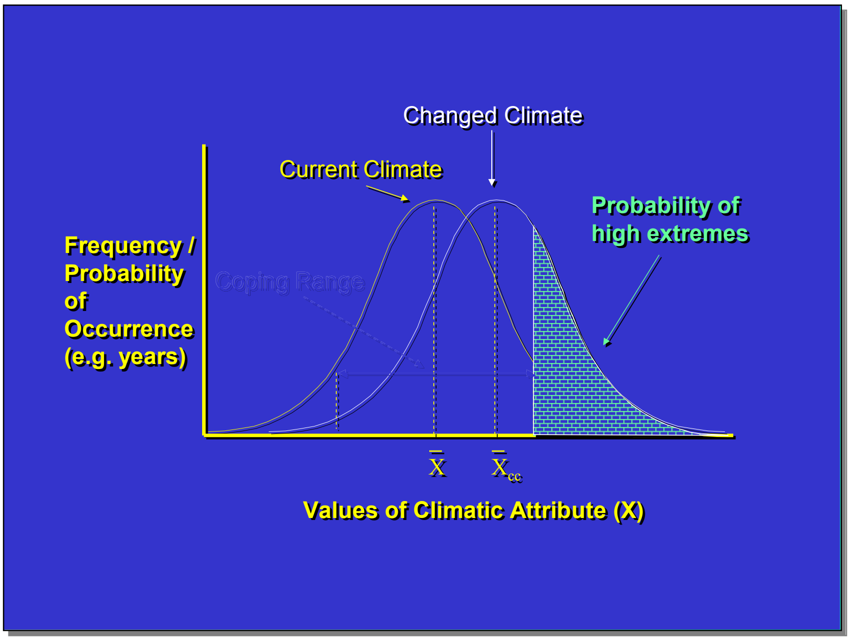


Figure 3.5 Schematic change in frequency distributions with increases in means (after IPCC-WG1, 1990)

3.1.5 These changes in the climatic drivers of the hydrological system (ΔCO_2, ΔT, ΔP) take on different regional significances in South Africa because of different individual and local sensitivities to change[2]

From a series of sensitivity analyses performed on mean annual runoff (MAR) with the *ACRU* model on the 1946 Quaternary Catchments covering South Africa, Lesotho and Swaziland (Schulze and Perks, 2000), the following are shown in Figure 3.6:

- ***a doubling of atmospheric CO_2 concentration***, by itself, i.e. with no changes to the two other climate change drivers P or T, is relatively insensitive, with the transpiration feedback resulting in generally small increases in MAR, but up to 8% in parts of the Western Cape province, the coastal areas of KwaZulu-Natal and the Mpumalanga Drakensberg;

- ***an increase in temperature by 2°C***, by itself, through increases in potential evaporation and resultant reductions in antecedent soil moisture, reduces MAR, with high sensitivities and MAR reductions over 25% in parts of
  - the winter rainfall region of the Western Cape province and
  - the Drakensberg of Lesotho/KwaZulu-Natal

  because in both those regions a 2°C increase "flips" a threshold of low temperatures to values above that at which atmospheric demand changes are relatively high; and
- ***a unit change in rainfall***, by itself, is highly sensitive with changes in runoff by 2-4 times the change in rainfall over most areas, and with a 4-5 fold sensitivity along the South African west coast.

Particularly trend changes in temperature and, even more so, rainfall patterns could have major implications to water resources planners, some of which are discussed next.

3.1.1 Impacts of climate change may be felt sooner over South Africa than we wish, with impacts not spread evenly across the country[2]

A threshold analysis was undertaken over South Africa on possible impacts of climate change on MAR by inverting the conventional question of ***what*** the change is likely to be to ***when*** a significant change in MAR might occur, and ***where*** first. This analysis applied the Had2CM GCM for a 2 x CO_2 equivalent climate change scenario for southern Africa, using a method of GCM output time slicing described by Schulze and Perks (2000).

If a 10% change in MAR were to be considered "significant", then Figure 3.7 shows that the western third of South Africa could be impacted by 2015 already, with the impact generally occurring later as one moves northeastwards.

Both this analysis, using an actual GCM output for a 2 x CO_2 scenario and regionally varying ΔT and ΔP in interaction with one another, and the sensitivity analysis on climate change drivers (but without any interactions), point to water resources planners in the Western Cape as having to factor in possible climate change impacts to hydrological responses sooner than elsewhere in the country.

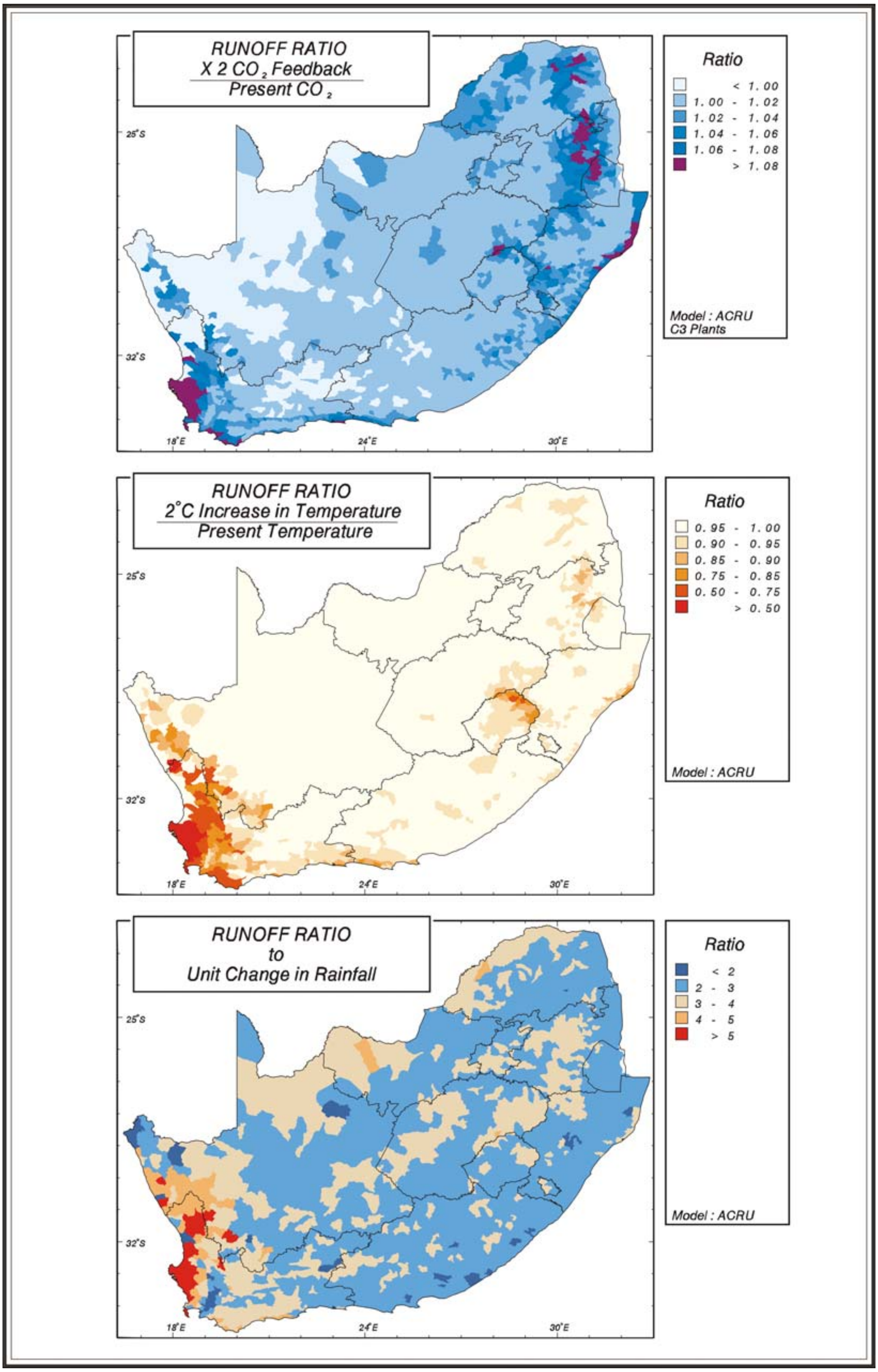


Figure 3.6 Sensitivity of changes in CO_2, temperature and rainfall on mean annual runoff over southern Africa (after Schulze and Perks, 2000)

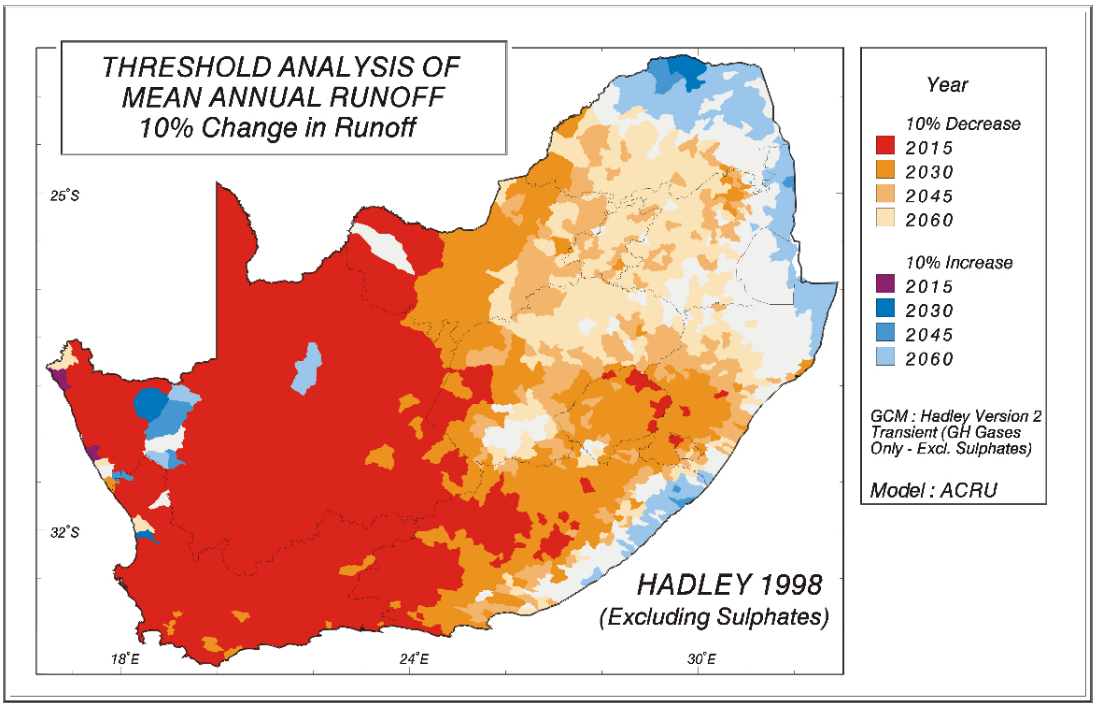


Figure 3.7 Threshold analysis on when a 10% change in MAR could occur in southern Africa, using the HadCM2 General Circulation Model (Schulze and Perks, 2000)

3.1.6 Water resources planners cannot view climate variability (CV) and climate change (CC) impacts on hydrological responses in isolation, without considering additional impacts CV/CC may have on shifts in baseline land cover and on land use patterns[2]

In water resources one needs to evaluate both

- ***impacts of water availability ON land use***, i.e. viewing climate and water as a limiting factor, and
- ***impacts of land use ON water availability***, in which case land use becomes the limiting factor on water, as with irrigation or intensifying biomass, e.g. plantation forestry.

Impacts of land use on hydrological responses are frequently assessed against responses from a baseline land cover, e.g. natural vegetation. However, with any climate change the natural vegetation will respond dynamically on both inter-annual and decadal scales. Through grassland/woody species interactions, certain species may invade into new areas and the niche climates of biomes/vegetation types may shift geographically. This implies, *inter alia*, that with climate change the ***baseline land cover*** against which hydrological impacts are assessed ***will change*** - a factor which complicates any realistic impact studies of climate change in hydrology.

Additionally, there may be major or minor ***shifts in climatically optimum growing areas of crops***. Certain crops are relatively robust to climate change and may only display minor shifts in climatically optimum growing areas (e.g. kikuyu pasture), others are relatively sensitive (e.g. sorghum) while others again are highly sensitive (e.g. certain tree plantation species) and may move to areas barely overlapping with present growing areas (Figure 3.8). These changes in spatial distributions are likely to have major hydrological implications.

3.1.7 Many uncertainties remain in regard to potential impacts of climate change on water resources[2]

***Uncertainties still abound around the question of climate change*.** These start with uncertainties in emission scenarios of greenhouse gases, with further uncertainties in global change sensitivity which "explodes" at the level of regional changes, climate variability, then biophysical impacts and eventually socio-economic impacts (Figure 3.9). In a probabilistic manner this "growth" of uncertainties is illustrated in Figure 3.10. Uncertainties include questions on

- what is "noise" (i.e. natural variability) vs what is already a clear "signal" (i.e. trend) in an already variable climate, or
- the different GCMs at present only being able to predict general directions (e.g. temperature increases), sometimes even still give mixed signals, and varying magnitudes of change (e.g. on rainfall), and not yet with high degrees of accuracy on changes in variability (which are often more important in hydrology than changes in magnitude), or on local (vs global) change.

Other uncertainties in hydrology revolve around

- stochasticity, i.e. the inherent unknowable randomness of, for example, rainfall
- ignorance, i.e. imperfect knowledge of hydrological system dynamics and
- scaling issues, i.e. upscaling of process representation and downscaling of GCM information, as illustrated in Figure 3.11.

In regard to issues on climate change and hydrology some ***skeptics maintain*** **that**

- hydrological design is, at best, still an approximation only, with safety factors already built in, - or that Africa has more pressing water problems than those related to climate change, or that
- impacts of water engineering (e.g. of reservoirs, inter-basin transfers) are generally greater than those of land use change which, in turn, are generally greater than those of climate change (Table 3.1; Schulze, 2001), but with a high dependence on the scale at which the water resources are managed.

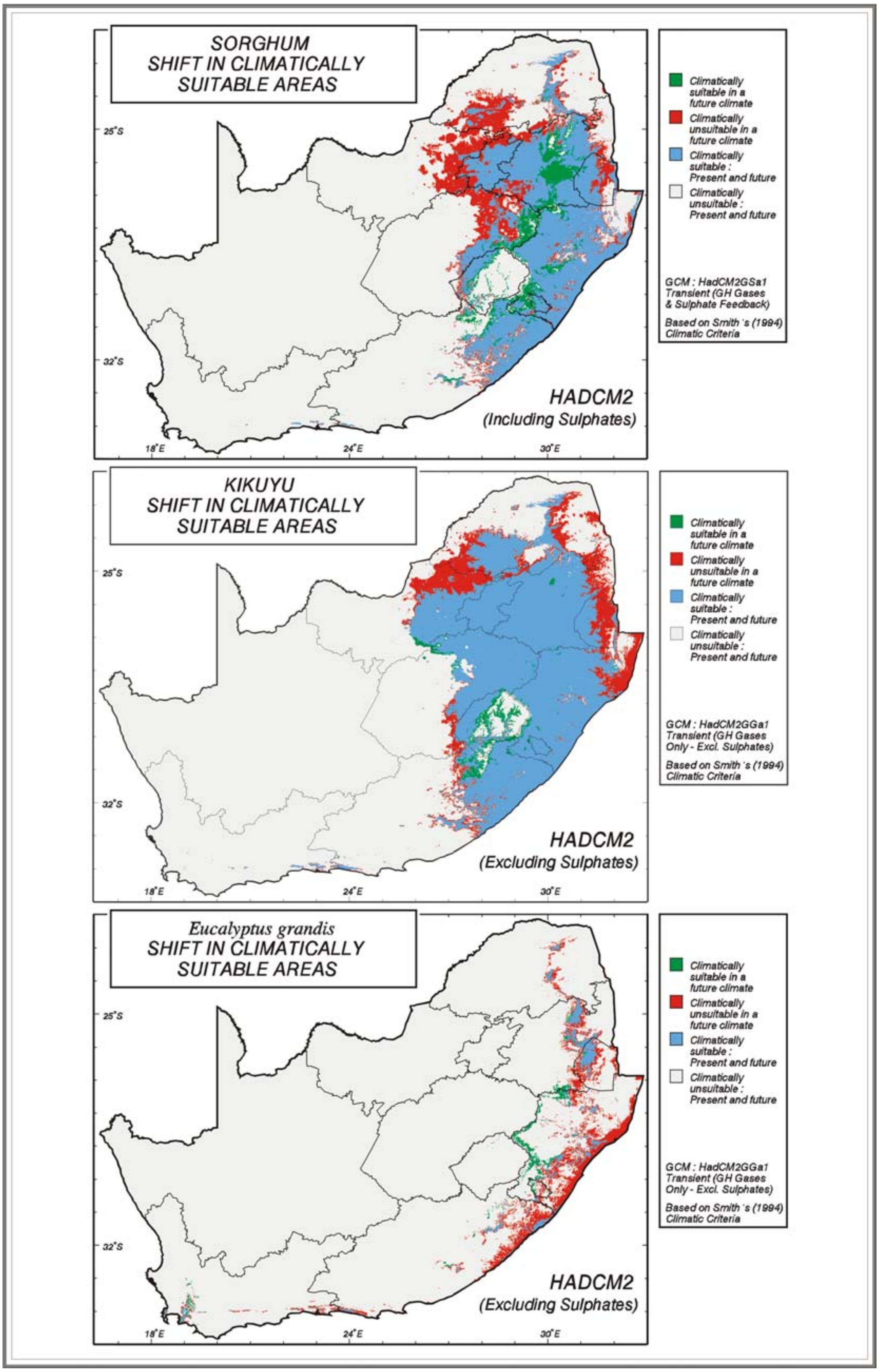


Figure 3.8 Simulated shifts in climatically optimum growth areas for selected crops over South Africa with climate change (Perks, 2001)

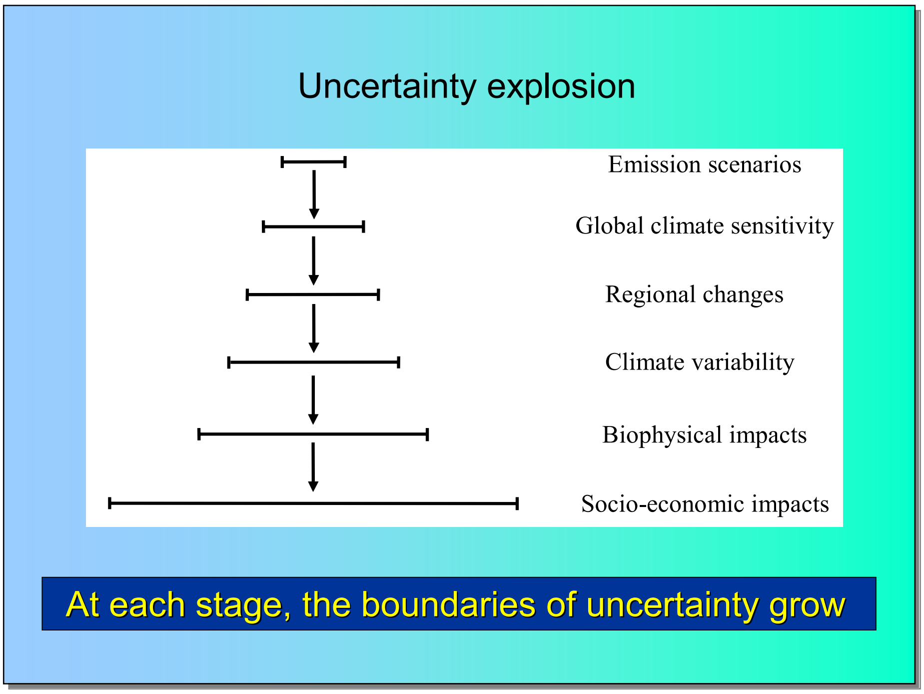


Figure 3.9 Schematic of the uncertainty "explosion" we have to consider in climate change impact studies (after Hewitson, 2002)

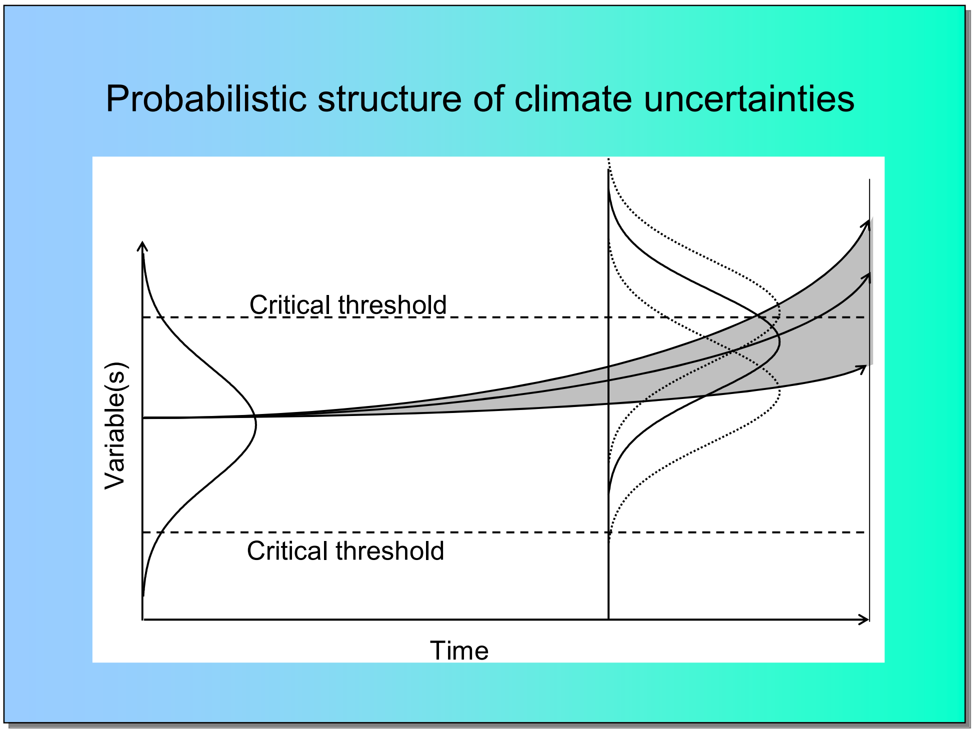


Figure 3.10 The probabilistic structure of climate uncertainties (after Hewitson, 2002)

Table 3.1 The link between climate variability and change with other drivers of the hydrological system at different scales (Schulze, 2001)

DRIVER	LAND- AND WATERSCAPE Process, Action, Structure	Cross Cutting Themes	SCALE		
			Small Catchment	River Basin	Conti-nental
ATMOSPHERIC DRIVERS (including climate variability, forecastability and change)	**NATURAL LANDSCAPE**	Integrated Water Resources Management; Rehabilitation & Renaturalization of Riverscapes and their Catchments			
	Topography & its heterogeneity		✓	✓	
	Soils & their heterogeneity		✓	✓	
	Natural cover & its heterogeneity		✓	✓	
	Overland flow generation		✓	✓	
	Unsaturated zone processes		✓	✓	
	Subsurface stormflow		✓	✓	
	Groundwater recharge		✓	✓	
	Soil loss & sediment yield		✓	✓	
	Biogeochemical processes		✓	✓	
	Flow routing - channel			✓	✓
	Transmission losses			✓	✓
	Floodplain/Wetland exchanges			✓	✓
	Sediment routing			✓	✓
	Estuarine processes			✓	✓
ANTHROPOGENIC DRIVERS (including socio-economic development)	**ANTHROPOGENIC LANDSCAPE**				
	Dryland cropping		✓	✓	✓
	Plantation forestry		✓	✓	✓
	Nutrient dynamics		✓	✓	✓
	Urbanisation / industry		✓	✓	
	Mining		✓	✓	
DIRECT WATER MANAGEMENT	**WATER AND RIVER ENGINEERED LANDSCAPE**				
	Groundwater abstractions		✓	✓	
	Irrigation		✓	✓	
	Channel modifications		✓	✓	
	Water storages and releases			✓	✓
	Water diversions (incl. transfers)			✓	✓

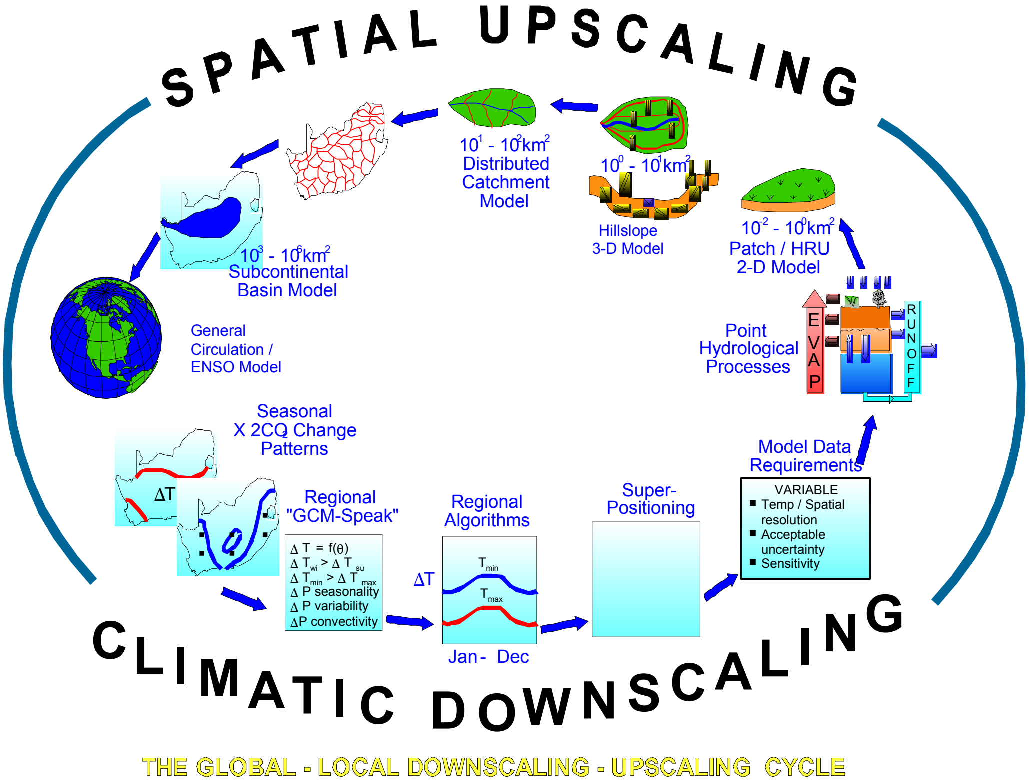


Figure 3.11 Uncertainties in climate change impacts in hydrology illustrated by spatial upscaling from point through catchment to the global, and climatic downscaling from global to local (Schulze, 1997b)

3.1.8 There are, nevertheless, sound reasons to adopt a no-regrets approach[2]

However, there are ***sound reasons to adopt a no-regrets approach*** to potential hydrological impacts of climate change, because

- hydrological structures
  - have long lead times
  - are often designed for lifespans of 50-200 years
  - are very expensive and essentially irreversible investments which
  - are designed to operate close to their design limits in times of major floods or droughts;

  furthermore, the
- hydrological system amplifies any changes in climate, implying that the assumption of climatic stationarity, used in current hydrological design, is invalidated
- the public expects efficient, robust designs to function into a future which may include climate change and
- decision makers need to ***justify*** their water structures ***decisions now, and for local conditions*** and cannot stall decisions until more certainty is available on climate change.

To ignore possible impacts of climate change on hydrological responses is, therefore, done at peril.

4. COPING WITH, ADAPTATION TO, AND PREPARING FOR, THE FUTURE

4.1 IS ADAPTATION NEW?[1]

Adaptation and coping strategies are not new. Since the time of Noah's flood, societies and civilisations have adapted to the vagaries of climate variability through various coping mechanisms and adaptation strategies. Societies and political systems were organised around the need to control, regulate and distribute water for irrigation and food production. Hence, coping and adaptation strategies are as old as civilisation itself. What are new are the improved technologies that allow for more efficient use of water in industry, households and agriculture, as well as more efficient water management systems (e.g. storage, conveyance, and treatment). In Noah's time it took a providential hint to build a boat in time to escape the flood. Today, people rely on early warning systems and flood forecasts to warn them of an impending flood.

4.2 ARE THERE REASONS TO ADAPT TO CLIMATE CHANGE IN ANY EVENT?[2]

The Intergovernmental Panel on Climate Change (IPCC, 2001) lists six reasons to adopt adaptation strategies to possible climate change NOW, irrespective of when, where and if climate change is going to impact a certain region (Box 4.1). These six reasons need ideally to be adapted specifically to water resources.

Box 4.1 The IPCC's (2001) six reasons to adapt to climate change now

1. *Climate change cannot be totally avoided.*
2. *Anticipatory and precautionary adaptation is more effective and less costly than forced, last-minute, emergency adaptation or retrofitting.*
3. *Climate change may be more rapid and more pronounced than current estimates suggest. Unexpected events are possible.*
4. *Immediate benefits can be gained from better adaptation to climate variability and extreme atmospheric events.*
5. *Immediate benefits also can be gained by removing maladaptive policies and practices.*
6. *Climate change brings opportunities as well as threats. Future benefits can result from climate change.*

4.3 BUT, DO WE OR DON'T WE ADAPT SPECIFICALLY TO CLIMATE CHANGE IN WATER RESOURCES MANAGEMENT?

4.3.1 What views are held by experts?[1]

Water resources engineers have always dealt, either implicitly or explicitly, with climate variability. For example, both ground and surface water storage help to mitigate against water shortages during dry spells by capturing and storing the water during wet periods. In light of this, Stakhiv (1998) brings the following question to the fore:

> *The question is whether the current methods of water resource development and management, based on the assumption of a stationary climate, can be suitably employed to accommodate the uncertainties of a non-stationary climate. Several authors, notably Fiering and Matalas (1990), Rogers and Fiering (1990) and particularly Matalas (1997) believe that the framework of stochastic (synthetic) hydrology, that is widely used in project planning, can accommodate the uncertainties in water supplies induced by global warming with the operational assumption of stationarity as meaningfully as with the assumption of non-stationarity.*

Gleick *et al*. (2000), on the other hand, argues that sole reliance on traditional management responses is a mistake:

- *First, climate changes are likely to produce – in some places and at some times – hydrological conditions and extremes of a different nature than current systems were designed to manage;*
- *second, climate changes may produce similar kinds of variability but outside of the range for which current infrastructure was designed and built*
- *third, relying solely on traditional methods assumes that sufficient time and information will be available before the onset of large or irreversible climate impacts to permit managers to respond appropriately; and*
- *fourth, this approach assumes that no special efforts or plans are required to protect against surprises or uncertainties.*

Both statements argue that the assumption of climatic stationarity is no longer valid in water resources management. The primary insight from this would seem to be the necessary commitment to a 'no regrets' policy of integrated water resource management, which inherently contains the flexibility and robustness to withstand all but the severest climate change scenarios. In addition, sensitivity analyses conducted on watersheds and river basins under a variety of scenarios may help to refine the operation and design of these systems for even greater resiliency (Stakhiv, 1998). In reference to the above statements, Gleick (2000) stresses that complacency on the part of water managers, represented by the third and fourth assumptions [in the quotation], may lead to severe impacts that could have be mitigated or prevented by cost-effective actions taken now.

4.3.2 …And what wise advice has been given?[1]

Klemes' (1991) list of ways to cope with climate change in water resources engineering includes:

- adherence to high professional standards in proposing solutions to existing water resource problems
- commitment to measures which limit water waste and pollution
- striving for robust and resilient designs
- documenting and taking into account known uncertainties in water supply and demand
- documenting the ranges of feasible operation of a projects, rather than providing only normal design parameters
- providing a general outline of feasible contingency measures for extreme conditions not accommodated by the project under normal operation (flexible operation rules) and
- insistence on clear disclosure of factual information, assumptions and conjectures behind modelling results.

4.4 WHAT DOES THE INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE RECOMMEND BY WAY OF ADAPTATION FOR WATER RESOURCES MANAGEMENT?[1]

Table 4.1 shows the IPCC adaptation recommendations for water resources managers. Note that there are, indeed, no major changes in coping with enhanced climate variability and climate change compared to what is being done (or should be done) in Integrated Water Resources Management already. The determination of the necessity of these measures will vary depending upon whether or not (and to what degree) climate variability and change are taken into account, i.e. the amount of variability and the level of an unexpected event.

4.5 IS THERE A "BEST STRATEGY" FOR ADAPTATION?[1]

The permutations for coping with the uncertainties of climate change and variability are limitless – both in the number of strategies and in the combinations of management measures that comprise a strategy. There is no single 'best' strategy for adaptation. Each depends on a variety of factors, e.g. economic efficiency, risk reduction, robustness, resiliency or reliability.

Table 4.1 IPCC recommendations for water resources managers (Modified from Table 4-13; IPCC, 2001)

Option	Comment	Option	Comment
SUPPLY SIDE		**DEMAND SIDE**	
▪ Increase reservoir capacity	▪ Expensive; potential environmental impacts	▪ Incentives to use less (e.g. through pricing)	▪ Possibly limited opportunity; needs institutional framework
▪ Extract more from rivers or groundwater	▪ Potential environmental impacts	▪ Legally enforceable water use standards (e.g. for appliances)	▪ Potential political impact; usually cost-inefficient
▪ Alter system operating rules	▪ Possibly limited opportunity	▪ Increase use of grey water	▪ Potentially expensive
▪ Inter-basin transfers	▪ Expensive; potential environmental impacts	▪ Reduce leakage	▪ Potentially expensive to reduce to very low levels especially in old systems
▪ Desalinisation	▪ Expensive (high energy use)	▪ Development of non-water-based sanitation systems	▪ Possibly too technically advanced for wide application
		▪ Seasonal forecasting	▪ Increasingly feasible
INDUSTRIAL AND POWER STATION COOLING			
▪ Increase source capacity	▪ Expensive	▪ Increased water-use efficiency and water recycling	▪ Possibly expensive to upgrade
▪ Use of low-grade water	▪ Increasingly used		
HYDROPOWER GENERATION			
▪ Increase reservoir capacity	▪ Expensive; potential environmental impacts; may not be feasible	▪ Increasing efficiency of turbines; promote energy efficiency	▪ Possibly expensive to upgrade
NAVIGATION			
▪ Build weirs and locks	▪ Expensive; potential environmental impacts	▪ Alter ship size and frequency	▪ Smaller ships, more trips; increased emissions and costs
POLLUTION CONTROL			
▪ Enhance treatment works	▪ Potentially expensive	▪ Reduce volume of effluents to treat (e.g. charging discharges)	▪ Requires management of diffuse sources of pollution
		▪ Catchment management to reduce polluting runoff	▪ Requires buy-in from farmers, e.g. incentives
FLOOD MANAGEMENT			
▪ Increase flood protection (levees, reservoirs)	▪ Expensive; potential environmental impacts	▪ Improved flood warning and dissemination	▪ Technical limitations in flashflood areas and unknown effectiveness
▪ Catchment source control to reduce peak discharges	▪ More effective for small than large floods	▪ Curb floodplain development	▪ Potential major socio-political problems
IRRIGATION			
▪ Increase irrigation source capacity	▪ Expensive; potential environmental impacts	▪ Increase irrigation-use efficiency	▪ By technology or increasing prices
		▪ Increase drought-tolerant varieties	▪ Genetic engineering is controversial
		▪ Change crop pattern	▪ Change to crops which need less or no irrigation

4.6 INTEGRATED WATER RESOURCES MANAGEMENT (IWRM) AS A PREREQUISITE FOR COPING AND ADAPTATION

4.6.1 What is Integrated Water Resources Management (IWRM)?

4.6.1.1 What is the core of IWRM?[1]

The core of water management has been its historically evolving adaptive capacity and capability. It is redundant to think of adaptation and coping strategies for climate change as something new, or apart, from basic water management practices.

4.6.1.2 What about management and climate change? The "no regrets approach" or the "precautionary principle"?[1]

Currently, there are no management options that are uniquely suited for adaptation to climate change that would be measurably different to those already employed for coping with contemporary climate variability. The only substantive difference is whether one adopts a more conventional and incremental

- ***no regrets approach***, where no regrest measures are those whose benefits equal or exceed their cost to society, i.e. measure worth doing anyway or a more anticipatory
- ***precautionary principle***, i.e. a process through which stakeholders influence and share control over development initiatives and the decision and resources which affect them. It is a process which can improve the quality, effectiveness and sustainability of projects and strengthen ownership and commitment of government and stakeholders.

4.6.1.3 How has our understanding of WRM changed over time?[1]

Clearly, water management practices and preferences have changed over time, for example, from 'hard' structures (dams, levees) to 'softer' solutions (floodplain relocation). The range of solutions and strategies has been broadened over time by improvements in technologies and availability of cheaper energy. However, very few of the traditional measures have been discarded from a growing toolbox of management measures of which the utility and cost-effectiveness has been demonstrated in numerous settings. What has changed is our understanding and implementation of the integrated ensemble of water management measures that conform to modern principles and policies. A catchment is composed of many users, upstream and downstream of one another. The integrated approach considers the catchment as a whole, and the impacts that changes in the catchment or the distribution of water will have on the other users. Water resources managers no longer start with the presumption that certain structural measures (e.g. dams, levees) are the best solutions. Rather, they begin planning by asking what the objectives for management are. These usually nowadays include such factors as social and community well being, womens' roles in water user groups and environmental restoration. Integrated Water Resources Management (IWM) is now the encompassing paradigm for adaptation to contemporary climate variability, and it is the prerequisite for coping with the still uncertain consequences of global warming, climate changes associated with it and their repercussions on the water cycle.

4.6.1.4 What are the requirements of IWRM?[1]

IWRM requires the harmonisation of policies, institutions, regulatory frameworks (e.g. permits, licences, monitoring), planning, operations, maintenance and design standards of numerous agencies and departments responsible for one or more aspects of water and related natural resources management. Water management can work effectively (but not efficiently) in fragmented institutional systems (such as those of the USA, UK and Western Europe), where there is a high degree of transparency in decision-making, public participation as well as adequate financial support being available for planning and implementation. It does not work well in most other cases where these prerequisites do not exist. Setting up the proper institutional framework is the first step towards IWRM.

4.6.1.5 What are the levels of integration required?[1]

True IWRM requires at least 5 levels of integration:

- ***Vertical integration*** ranges from the lowest level of user to the top policymakers in a ministry and all levels of government; from irrigation district to municipality to regional administration to national water commission.
- ***Horizontal integration*** implies co-ordination and collaboration among all the institutions responsible for resources management at a catchment scale.
- ***Interdisciplinary integration*** involves all relevant disciplines, including socioeconomic, engineering, hydrological, economic and ecological.
- ***Functional integration*** includes planning, regulatory, design, operations, maintenance and monitoring.
- ***Stakeholder integration*** involves non-governmental interests, user groups or native groups, in all aspects of water management and decision-making.

4.6.1.6 How are the requirements for IWRM best managed?[1]

Usually the complex, intersecting requirements of IWRM are best managed through a permanent co-ordinating body such as a River Basin Commission or Catchment Management Agency, whose trained staff are versed in both the technical needs of water management as well as in the requirements for multiple layers of co-ordination.

4.6.1.7 What fundamental principles underpin IWRM?[1]

The hallmark of IWRM is the routine updating and incorporation of fundamental principles for modern water management, as well as improvements in technology. This progressive adaptation of policies, analytical tools and procedures increases the prospects for implementing socially acceptable water projects. It will simultaneously contribute to effective adaptation not only in response to shifting societal needs and preferences, but to climate variability as well, as better and more detailed information and longer hydrological and climate records are incorporated into the planning, design and operation of water resources systems. It is also the constant updating of socially determined management principles and planning objectives that define the evaluation context and rules which allow water managers to distinguish between various management measures and select those which are consistent with the planning objectives established through the public participatory process. These principles have been developed over many decades, and are derived from numerous international conventions. They have been codified as follows:

- Every person should have access to a safe and reliable source of water. Water is essential for food production and self-sufficiency.
- Water is a social and economic good, and its values must be taken into account formally in evaluating projects.
- Public participation is an essential component of effective water resources management and, particularly in Lesser Developed Countries (LDCs), all attempts should be made to engage women in water resources management.
- Water is managed most effectively at the level for which decisions and responsibilities are routinely exercised (principle of subsidiarity).
- Financial subsidies for water resources development should be minimised and costs should, where possible, be recovered in some form or other by the users to ensure efficient use of water.
- Present-day thinking is that privatisation of selected water resources management functions should be promoted to the extent possible in the developed sectors of economies, especially for vendible outputs and services, such as hydro-power, or irrigation, municipal and industrial water supplies. Privatisation in LDCs can, however, thwart rather than promote the development and well being of the poorer segments of society.

4.6.2 At what range of spatial scales does IWRM have to operate?[3]

Since catchment processes, including land use and socio-economic processes, take place at a range of spatial and temporal scales, the relevant scale for IWRM is not always clear. As a general statement, however, the appropriate temporal and spatial scales of operation of IWRM are those at which policy-makers, catchment managers and stakeholders of an IWRM plan believe they can achieve their objectives (Schulze, 2001).

In regard to spatial scale, Schulze (2001) lists issues of IWRM for several different scales:

- global scale issues, e.g. water conventions, climate change
- international scale problems, e.g. transboundary rivers
- national issues, e.g. national water management agendas of a country

- catchment scale issues
- local government scale initiatives
- community scale issues and
- household scale problems, e.g. in poorer countries where household food security or household water scarcity are major day-to-day issues.

The larger the spatial scale, the more difficult management becomes, according to Frost's (2001) observation in rural Africa. A larger scale implies a broader range of resources available, and of the number and diversity of stakeholders who have different skills, interests, resource endowments and management capacities. As a result, agreement and consensus is difficult when spatial scales are too large and plans of action become more complex and time consuming. At very fine scales, however, there is a danger of losing sight of the wider context and of the overall governing processes of IWRM.

4.6.3 At what range of temporal scales does IWRM have to operate?[3]

Similarly, temporal scale processes can also vary immensely, and need to be considered in the context of IWRM. With respect to the temporal scale Schulze (2001) lists:

- climate scales at decadal, inter-seasonal, intra-seasonal and event time frames, which 'drive'
- river flow scales, which range from multi-year cycles, to inter-seasonal variability, to intra-annual variability, to flash floods
- ecological time scales, which are determined by magnitudes, frequencies and durations of low and high flows as biological triggers
- agricultural time scales, where for crops the intra- and inter-seasonal timeframes are important, whereas for forestry inter-seasonal to decadal timeframes are of significance
- economic time scales, ranging from longer term international to national, regional to local to shorter term individual household time scales
- political time scales, which need to distinguish between essentially stable government structures vs. potentially unstable government structures, as well as distinguishing between inter-election time scales for national to local governance structures
- management and planning time scales, often of the order of 10-20 years and
- wealth/development level time scales, where wealthy countries tend to have longer term planning horizons while for poorer countries they tend to be shorter.

From the above list, it is evident that a wide range of temporal scales exists. The IWRM approach is not committed to one scale, but considers the overlapping time scales in an integrated fashion.

4.6.4 What distinguishes IWRM in Lesser Developed Countries from that in developed countries?[3]

The DWC is particularly focused on raising awareness in LDCs to the impacts of climate variability and climate change on the water resources. Although the approach to IWRM as described in the previous sections apply to LDCs as well, major differences exist in the way IWRM can be implemented there. Table 4.2 (Schulze, 2001) gives an overview of these differences. Generally, developed countries tend to focus more on quality of life, environment and on long-term issues while LDCs frequently have to address more basic day-to-day issues (Schulze, 2001).

With the tendency for concepts on IWRM to emanate largely from the developed world, a re-focus is necessary on problems of IWRM in LDCs. Schulze (2001) states the following generalities for LDCs:

- decisions on water management are often made 'from a distance' in a far-away capital city
- poor peoples' water needs are frequently overlooked or underestimated in broader scale IWRM
- amongst stakeholders there are major disparities in wealth, influence with government, opportunity, skills, resource endowments and capacity for management as well as for economic performance (Frost, 2001)
- government project failures abound because funds have run out, or they are behind schedule, or operation and maintenance are inadequate
- the main need is for basic infrastructure development to provide for water security and
- priorities pertaining to environmental issues are frequently lowered, and where considered, often focus on economic benefits such as erosion and river control.

Moreover, for many LDCs, changes in climate and its variability are just one of the many problems they are facing, and depending on the magnitude of these changes, are often not viewed as the most pressing. This should be taken into account particularly when climate change is discussed in the context of LDCs. Also, the 'solutions' that come out of the discussions must take the specific conditions of LDCs into account, for example:

- local catchment planning methodologies should be both technically sound and participatory, building on local peoples' (= vernacular) knowledge, experience and practice
- planning initiatives should be accessible to, and involve, local community organisations and which include appropriate capacity building and technical support and
- the framework of initiatives should encourage local-level collaboration amongst NGOs, CBOs (community-based organisations) and relevant government departments.

Table 4.2 Characteristics influencing IWRM in more developed vs lesser developed countries (after Schulze, 2001)

INFRASTRUCTURE	
▪ High level of infrastructural development with infrastructure generally improving	▪ Infrastructure often fragile and frequently in a state of retrogression
▪ Infrastructure decreases vulnerability to natural disasters (e.g. floods, drought)	▪ High vulnerability to natural disasters; heavy damage and high death toll
▪ High ethos of infrastructure maintenance	▪ Low ethos of infrastructure maintenance
▪ High quality data and information bases available, well co-ordinated	▪ Data and information bases not always readily available
CAPACITY	
▪ Scientific and administrative skills abundantly available	▪ Limited scientific and administrative skills available
▪ Expertise developed to local levels	▪ Expertise highly centralised
▪ Flexibility to adapt to technological advances	▪ Often in survival mode; technological advances may pass by
ECONOMY	
▪ Mixed, service driven economics buffered by diversity, highly complex interactions	▪ High dependence on land, i.e. agricultural production; at mercy of vagaries of climate
▪ Economically independent and sustainable	▪ High dependence on donor aid, NGOs
▪ Multiple planning options available	▪ Fewer options available in planning
▪ Take a long term planning perspective	▪ Take a shorter term planning perspective
▪ Countries wealthy, money available for planning and IWRM	▪ Wealth of countries limited, less scope for planning and IWRM
SOCIO-POLITICAL	
▪ Population growth low or even negative	▪ High population growth rates and demographic pressures on land
▪ Generally well informed public with good appreciation of planning	▪ Poorer informed public, less appreciation of science/planning
▪ High political empowerment of stakeholders	▪ Stakeholders often not empowered, afraid to act or to exert pressure
▪ Decision making decentralised	▪ Decision making centralised
ENVIRONMENTAL AWARENESS AND MANAGEMENT	
▪ High level of expectation of planning and IWRM	▪ Lower level of expectation and attainment of goals
▪ Desire for aesthetic conservation	▪ Need for basics for living

4.6.5 Has IWRM been successful?[1]

There are few countries in the world that have developed comprehensive national water management plans and strategies. In the absence of these, fragmented approaches by a proliferation of government agencies and other stakeholders make implementation of Integrated Water Resources Management difficult, at times impossible. For example, in Canada (as in several other countries) water is considered a natural resource under the jurisdiction of the provinces. The distribution of water resources and the demands vary widely. Legislation on environmental protection and even standards for drinking water also vary. This will make it very difficult for Canada to take positions in negotiating international agreements related to trade and which involve the concept of virtual water or water transfers. In most less developed countries, the policy and institutional frameworks are much weaker still.

There is almost unanimous agreement among water resources managers and the international community on the Dublin and Rio statements on holistic management (ICWE, 1992) and safeguarding basic needs and ecosystems. There probably is no country in the world, however, that has fully integrated them into their policy framework. The degree to which they can be implemented and put into practice depends on the adaptive capacity of countries' institutions. It is not surprising therefore, that developing countries are even further from reaching the ideal of IWRM than more developed ones.

4.6.6 And if not, why not?[1]

In response to water scarcity, the approach that is simplest to implement and meets the least resistance is to increase the production efficiency of water, e.g. by improving irrigation efficiency. This approach will, therefore, be the first choice of farmers, engineers and politicians alike. When this has proved to be inadequate, they will turn next to possible ways of allocating water among users. Somewhere around this time they will likely recognise that in satisfying the needs of society, they have done significant, if not irreversible, harm to the environment. At the next stage they may be forced to recognise that self-sufficiency is not possible, and that water must be imported - either physically (usually not cost-effective) or in ‘virtual’ form through goods and produce from other regions or countries. Each stage in this process is more difficult and involves more actors. Ultimately, the last stage requires international negotiations and co-operation.

The above approach may be described as ‘re-active’. IWRM, however, should be based on an approach that is ‘pro-active’, ‘anticipatory’, based on the ‘precautionary principle’, and include the application of preventative actions so that there are ‘no regrets’ throughout the process. If such an approach were taken, it would certainly, as noted above, create the resiliency to deal with the additional complications of global warming. The reality is that the ‘re-active’ approach is still the one that dominates, and is likely to continue to dominate, in the absence of long-term political leadership.

It is often noted that even when policies are in place, they are not implemented because one or more of the parties responsible for implementation fails to follow through. Political will and leadership are required also to overcome this implementation gap.

Up until recently there has been inadequate attention to the implications of the need for water for human uses, especially through agricultural production, and the need for environmental sustainability, i.e. two of the Rio principles. More research and discussion will be required to develop policy alternatives and strategies in order to manage water to meet these competing basic needs so as to reduce the uncertainties and ambiguities surrounding this issue. There are ongoing debates too about appropriate policies and strategies to ensure equitable access to water, especially for the poor. Finally, there still is a need to develop appropriate strategies and policies to deal with floods and droughts, even in the absence of climate change.

4.6.7 What are the barriers of success to IWRM?[3]

Identification of problems is prerequisite to identification of solutions. There are several barriers that can limit the effectiveness of the role of political institutions in managing the water resources in general, but particularly in light of climate change and variability. These include (Schulze, 2001):

- Sectoralism within and between the government departments and the fragmented nature of institutional structures, e.g. each with different functions as well as different political goals and each with different stakeholders, with 'control' of a water sector often being more important than integration, with poor inter-agency linkages between risk management vs water resources vs irrigation vs land management vs international obligations and with effective strategising on climate change impacts then falling through the cracks
- Lack of clearly defined overall strategies, including management objectives, mechanisms for delivery to enable objectives to be achieved, and being 'high on rhetoric' and talk at strategic level and 'low on action' on the ground
- Lack of research to assess the resource base with respect to water resources availability and risk, and the value of water in terms of economic production (e.g. $/m^3 water or t/ m^3 water), or consideration of the entire hydrological cycle
- Water being a source of conflict, not only between sectors (e.g. rural vs urban) but also within a sector (e.g. dryland vs irrigated agriculture; commercial vs subsistence agriculture), but in particular with respect to upstream/downstream users and uses
- Deficiencies in information, which can imply insufficient spatial information, and/or a lack of willingness among organisations to share data and information , and/or data/information not collated, out of date or not disseminated because it resides in obscure reports or theses, and/or networks of information flows being inadequate
- Deficiencies in capacity, with regard to human capacity to effect coping strategies on climate variability and change, or capacity being too centralised in certain institutions
- Deficiencies in land management options, including how to use land impacts on quantity and quality of water under variable climate, how to cope with/adapt to

changing hydrological conditions with respect to inter-annual climate variability or more permanent climate change, and trade-offs between land use practices, either within a sector and between sectors, in light of climate change

- Lack of willingness to integrate, e.g. with land users and land use agencies each still seeking to assert their primacy in relation to how the land and its associated water resource should be used, or in regard to political power plays existing between individual disciplines involved in IWRM and their distinctive methodologies of seeking solutions to coping mechanisms (e.g. types of and approaches to modelling, or the use of 'hard' vs 'soft' tools) and
- Lack of audit and post-audit procedures, which embrace, *inter alia,* who is going to enforce and 'police' progress in coping strategies as well as who will critically evaluate the performance of actions during and after an extreme event.

4.6.8 What new paradigms are needed to address these barriers?[1]

In order to address the above barriers, political institutions need to adopt new paradigms, which include (Pahl-Wostl, 2002a):

- changing the technology-driven tradition of water resources management to an integrated management perspective where the human dimension has a prominent place
- adopting a new and comprehensive notion of policy and polycentric governance that includes the design of flexible and adaptive human-technology-environment systems (of particular importance in times of increasing uncertainty due to climate change)
- bridging the science-policy gap by defining a new role for science as an active participant in polycentric policy processes, rather than being an external observer and
- developing new concepts and methods for public and stakeholder participation in multi-scale integrated assessment processes and modelling.

In order to improve the capacity to cope with climate variability through the political and institutional dimension, a wide range of aspects need to be addressed, involving economic, institutional, social and political aspects. These aspects are worked out in the following sections.

4.6.9 What economic aspects are at play in IWRM?[1]

As a consequence of climate variability and climate change a wide range of water-related products and services are at risk. The concept of virtual water trade can provide a network to absorb climatic shocks. For countries to take part in the network of virtual water exchange they need to have access to markets and to be part of a system were a minimum of economic and political stability is guaranteed. In the North an example of such a system is the European Union (EU), which developed from a common market into a political union. SADC and ASEAN (in the Far East) have taken similar steps, although the process is not yet as advanced as in the case of the EU.

Economic incentives and market-based instruments play an important role. However, dealing with water as an economic good is not free of controversies. For example, there is a major difference whether water is required for survival or if it is used for leisure purposes. The lack of access to financial resources and market power should not prevent underprivileged groups in a society from their access to water as an essential resource.

Water is distributed unequally among the regions of the world. Whereas water markets and participatory water resources management (through, say, water user associations) may be quite efficient at allocating water among different competing demands on a regional scale, water is not a commodity that can be traded at a global scale. Here the importance of virtual water comes into play. The supply of the megacities of the world will have to be based on a global supply network. Given the potential and/or the perceived increase in vulnerability that may arise from the dependencies in global supply networks, resolving this issue will require a multi-scale participatory process with numerous stakeholders involved.

4.6.10 What institutional capacity is required for IWRM?[1]

There is a need for a community of water professionals that is fully conversant with the concepts of IWRM and which operates within a network of stakeholders, officials, researchers and educators.
Such networks of institutions and individuals can be powerful mechanisms to plan coping strategies for, and thereby absorb shocks related to, water and climate related issues such as floods, droughts, pollution hazards and allocation conflicts. Often, it takes a major catastrophe to stimulate the creation of such a network.

4.6.11 If water management is to be participatory…

4.6.11.1 Who are the main stakeholder groups?[1]

The process of water resources planning and decision making should be shared with the four main stakeholders in society: civil society, the private sector, NGOs and the relevant government entities. Only if these four groups of actors are actively involved in a participatory process can the process become efficient in addressing the challenges in water resources management.

It is imperative that participation addresses needs and aspirations of both stakeholders and the public at large. Stakeholders should be distinguished from the public at large. A stakeholder is only defined in reference to a particular issue. Public and stakeholder participation has to be based on careful analysis of the current institutional setting (the roles of different stakeholder groups, formal and informal rules, and types of organisation) and a subsequent design of a participatory process.

4.6.11.2 What is the participatory process?[1]

The participatory process contains certain formal relationships, e.g. public authorities that have formal, legal and/or contractual relationships. In particular, however, it must address groups that communicate only informally, or do not generally communicate at all, but who are affected by an integrated management approach. The latter participatory process will have to proceed with the implementation of novel policies and/or institutional settings. Any water resources management plan that includes environmental, economic and social objectives, as well as changes in technological and institutional settings, has to be developed in a participatory setting. This will guarantee that those issues relevant to the actors are captured. Additionally, the participatory process must take into account the importance of procedural implications, e.g. that the preferences regarding an outcome of a decision are highly dependent on how the decision was derived (Joss and Brownlea, 1999).

4.6.11.3 What does co-operation imply?[1]

Co-operation will play an important role. The importance of co-operation and the difficulties in achieving it have been on the research agenda of the social sciences for many years already (key phrase: ‘tragedy of the commons’). It is now well recognised that trust, reciprocity and reputation are norms that have to be shared by a collective of actors in order to achieve voluntary agreements, engage in co-operative action, adopt novel strategies and escape from situations of social dilemma (Ostrom, 1990; 2001).

4.6.11.4 What is the role of citizens?[1]

The lack of information and the lack of an ability to make decisions often prevent citizens from becoming more involved. In contrast, empowerment implies that citizens really take an active role in defining an issue. This active role embraces a number of important points:

- Citizens need access to comprehensive and timely information about an issue.
- Different perspectives and uncertainties on the issue must also be provided.
- Citizens have to be enabled to take over responsibility in important decisions.
- Institutional settings must permit citizens to phrase and communicate their perspective and to articulate their voice clearly.
- Citizens must have a real stake in an issue to be motivated to make an active contribution.

Citizens should be involved in different arenas of decision making in water resources management. On the one hand, they may participate in making choices on transformation processes towards entirely new management schemes. On the other hand they may become active participants in daily management practices. Hence, one can make a distinction of three different areas for citizen participation (Pahl-Wostl, 2002b), *viz.*

- ***integrated assessment***, where informed citizens judge risks and benefits of different development trajectories and management schemes
- ***technology assessment***, where single technologies and their risks and benefits are judged and
- ***risk management***, where citizens take an active role in assessing and managing risks on a routine base.

4.6.12 What is government's role in IWRM?[1]

Governments should share the burden of managing the resource with the other actors in society, particularly with civil society, the private sector and NGOs. Government should be the director of this process, taking on the roles of:

- ***Caretaker***, responsible for the conservation and wise use of the natural resources
- ***Regulator***, to safeguard the public interest and to enforce the law and
- ***Facilitator***, to facilitate that the other actors play the role they need to play.

Concepts of good governance are important aspects in this regard, through the provision of legal security, transparency, accountability and the freedom to express one's views.

The role of water policy in the light of an integrated management of water resources at different scales implies the need to manage major societal transformation processes towards sustainability. In such cases, it is important to adopt a broad understanding of a polycentric policy making. Polycentric governance involves processes of social learning that are essential for processes of innovation and the adoption of new strategies in heterogeneous actor networks (Pahl-Wostl, 2002b).

This implies that a command and control approach that characterised environmental policies in a number of countries (including some in the EU) in the past has to be replaced by the use of market-based instruments in combination with incentives for self-organisation and public participation. This also reflects a changing role for the government and is now characterising the new European Water Policy (Philip, 1998).

Finally, government should promote the development of coping strategies by supporting research, pilot projects and mainstreaming good management practices.

4.7 WHAT ROLE CAN CLIMATE FORECASTING PLAY AS AN ADAPTATION STRATEGY?

4.7.1 There are strategic, tactical and operational forecasts[2]

There are many decisions based on climate and weather conditions that need to be made and at various scales. They may be classed into three types of decisions (Figure 4.1):

- ***Strategic*** decisions would be those linked more to long term climate change over a number of years.
- ***Tactical*** decisions would be linked more to medium term forecasts, i.e. the seasonal forecasts of rainfall over a number of months.
- ***Operational*** decisions are concerned with short term weather forecasts and their implications on day-to-day water resources operations.

Type of Decision	Climate		Weather
	Long Term	Medium Term	Short Term
	Climate Change	Seasonal Forecast	1-7 Day Forecast
Strategic			
Tactical			
Operational			

Figure 4.1 Types of decisions based on climate and weather (Schmidt, 2003)

4.7.2 Climate forecasts as an emerging technology[1]

It is clear that an emerging technology, which has the potential to improve virtually all forms of water management related to climate variability and change, is short-term meso-scale climate and hydrological forecasting for 15-, 30-, and 90-day periods. More reliable short-term weather forecasting for agricultural water management purposes represents a key example of how scientific breakthroughs can aid real-time water management and operations, which in turn improve the overall responses to climate variability and can greatly increase the efficiency of water management and use. This is especially the case for irrigation, which, globally, is by far the largest user of water. Although examples of the use of seasonal forecasts and their potential further use, as well as advances in institutional support are cause for optimism, use of climate forecasts in WRM is, in general, still too new to support the strong generalisations about its value (Hansen, 2002).

4.7.3 What do we mean by long, medium and short term hydrological forecasts?[4]

Long term hydrological forecasts typically have a lead time of a month or more. These can only give a general indication whether there would be a risk of increased flooding, e.g. due to ENSO, and if the coming floods are likely to be average, below or above average. These hydrological predictions depend very strongly on forecasting accuracy for weather and climate on seasonal time scales.

Medium term hydrological forecasts have a lead time of a few weeks, and should provide more accurate estimates of the flood conditions. These forecasts mainly depend on the quality of rainfall observation and information from the upper watersheds, additional short term climate information, and the quality of a distributed hydrological model used to calculate runoff and river flows.

Short term hydrological forecasts, with a lead time of a few days, focus on river water levels and the extent and depth of inundation areas. This forecast is derived from real-time observation of rainfall and river flow in the upper watershed, combined with hydrological and hydraulic models which calculate or estimate water levels in the river and water storage in the inundated areas.

4.7.4 What are the prerequisites for effective use of climate forecasts?[1]

Hansen (2002) lists five prerequisites for effective use of climate forecasts:

- Climate forecasts must address a need that is both real and perceived.
- Benefits of forecasts depend upon the existence and understanding of decision options that are sensitive to the incremental information that forecasts provide, and are compatible with decision-maker goals and constraints.
- Forecasts of relevant components of climate variability for relevant periods have to be at an appropriate scale, with sufficient accuracy and lead time for relevant decisions to be made.
- The use of climate forecasts requires that the right audience receives, and correctly interprets, the right information at the right time, in a form that can be applied to the decision problem(s).
- Finally, sustained operational use of forecasts beyond the life of a project requires institutional commitment to providing forecast information and support for its application to decision making, and policies that favour beneficial use of climate forecasts.

4.7.5 Why are the benefits of forecasts not yet utilised?[4]

Timely and reliable forecasts hold promise for improving economic and social well-being in both good and bad years. Nevertheless, if the consequences of accepting a given forecast are significant (e.g. water supply collapse in a major city), the forecast should be treated with caution. There is always a margin for error in any climate forecast, and users should always therefore think of adaptive and dynamic decision support systems which allow for alternative emergency pathways in case the forecast proves to be wrong.

While progress continues to be made in seasonal climate forecasting, the net benefits of using seasonal climate forecasts in water management still have to be better demonstrated. A number of factors are responsible for this situation (Bates, 2000):

- The inaccessibility of climate information and forecasts, and insufficient advocacy by climate scientists at local to international levels.
- Poor communication between water managers and climate scientists about their perceptions of research priorities and views on knowledge gaps.
- The complexity of the problems faced by water managers and the effects of political and institutional constraints on their decisions.

- Conservatism in the water sector towards funding development of new technologies and applying emerging technologies in practice, and scepticism about the accuracy and value of climate forecasts.
- Water managers have limited training in or experience with climate science.

These factors re-emphasise the need for regional water managers to share their experiences and commit to long-term dialogue with climate forecasters. Such a dialogue is necessary if climate forecasters are to build a comprehensive and accurate picture of the water managers' information needs, and for water managers to appreciate the scope and depth of recent advances in climate prediction science and the knowledge gaps that remain.

4.7.6 An example of climate forecasts in agriculture[2]

Table 4.3 Impacts of climate change and climate variability on the sugar industry: Mitigation and adaptive strategies and climate forecast requirements (Schmidt, 2003)

Impact of Climate Change and Climate Variability on Sugar Industry	Mitigating / Adaptive Strategy	What Forecast is Required	When
Strategic Decisions (Long Term Climate Change)			
Change in sugarcane production potential and between year variability (risk)	▪ Relocate, expand, contract production areas ▪ Adjust milling capacity ▪ Modify transport capacity ▪ Variety selection ▪ Modify crop cycle ▪ Pest and disease control measures	Climate Change	Current Assessment
Tactical Decisions (Medium Term Climate Forecast)			
Marketing Pricing, marketing, storage and distribution of sugar	▪ Price, forex, interest rate risk management ▪ Market selection ▪ Storage planning ▪ Transport scheduling	Seasonal Forecast	September (prev year) February (current year) Updated monthly
Milling Length of milling season Mill operation strategies	▪ Revise mill open and close dates for maximum recovery of sugar and use of investment ▪ Grower daily allocations ▪ Manage mill extraction performance	Seasonal Forecast	September (prev year) February (current year) Updated monthly
Farm management Harvest and haulage planning Crop husbandry Irrigation planning Cash flow management	▪ Plan labour and equipment requirements ▪ Decisions on harvest timing, harvest methods, replant areas, fertilizer amount and type, pest and disease control, carry over decisions, flower suppression ▪ Water orders and allocations, timing of applications, field selection, system operation ▪ Loan and investment decisions	Seasonal Forecast Monthly Forecast	February Monthly thereafter
Operational Decisions (Short Term Weather Forecast)			
Harvesting	▪ Mill stoppage (no cane stoppage) ▪ Machinery infield operation (compaction) ▪ Timing and size of area burnt (cane supply decisions, environmental impact decisions)	1-7 Day	Continuous
Field operations	▪ Timing of land preparation, planting ▪ Fertiliser application timing ▪ Chemical ripener and herbicide application timing	1-7 Day	Continuous
Irrigation scheduling	▪ Water orders ▪ Timing of irrigation and application amount ▪ Pump and equipment removal (flooding)	1-7 Day	Continuous

4.8 WHAT PLACE IS THERE FOR INDIGENOUS COPING STRATEGIES?[1]

Some 40% of the world's land area is located in environments which are prone to water scarcity. These areas host the hydro-climatic spectrum from arid to dry subhumid. The major characteristic of these landscapes, often denoted 'drylands', is not necessarily low total annual precipitation, but rather the high rates of potential evaporation experienced and the extreme spatial and temporal variability of precipitation. Coefficients of variation of inter-annual rainfall generally range from 20 – 40%, increasing with lower average annual precipitation. Societies evolving in these environments have, over centuries, developed a broad range of mechanisms to cope with climatic variability.

In rainfed based agrarian communities, which cover large parts of the semi-arid tropical world, this has focused on local development of social, economic and biophysical management strategies to bridge droughts and dry spells, and to cope with floods from intensive storms. The indigenous knowledge base on climatic coping strategies certainly dates back at least 7 000 years, which represents the most recent palaeo-climatic period with more or less constant natural climatic conditions (Nicholson and Flohn, 1980).

Indigenous strategies to cope with climatic variability vary between different geographical locations and between social-religious-cultural settings, as well as between livelihood cores (e.g. between agro-pastoral communities depending on livestock raising compared to sedentary farming communities depending primarily on crop production). It is thus impossible to give a generic overview of indigenous coping mechanisms. Suffice it to state that coping with climatic variability forms an inherent and fundamental part of societies hosted in arid, semi-arid and dry sub-humid temperate and tropical landscapes (Falkenmark and Rockström, 1993).

In a climate change scenario, climatic variability is expected to increase. This, according to several scientists, already has occurred. For example, in the Sahel rainfall averages since 1967 seem to have decreased 10 - 30 % compared to the long term average (Middleton and Thomas, 1992). With prospects of, or even experienced trends of, increased risks of extreme climatic variability, one would expect the proliferation of present and revival of old indigenous coping mechanisms. In general, however, the situation seems to be the reverse. Population pressure, degradation of land and water resources, and migration have, in large parts of the water scarce environments, resulted in a deterioration, and in many cases complete loss, of indigenous coping mechanisms.

From the birth of agriculture until recently in tropical environments (often until the late 19th century or even early 20th century) farming systems were based on shifting cultivation which depended on spatial rotation of cropland and long fallow periods. In environments with large spatial and temporal rainfall variability, this production strategy was strategically designed to spread risks in space and in time. In the Sahel, fallow based rainfed farming has essentially disappeared under the escalating pressure from population growth, and farmers depend for their livelihoods on continuous cultivation on small (far too small) parcels of land. Granaries were used as cereal banks, to store surplus grain from ‘wet’ rainy seasons for use during dry years, in accordance with Joseph’s advice to the Egyptian Pharaoh in the Old Testament (save the surplus from the 7 good years to cope with the 7 dry years which follow). This management strategy, dating back several millennia, formed the backbone of many farming systems in climatically variable environments until modern times.

In West Asia and North Africa coping strategies to deal with climatic variability and water scarcity date back at least to 5000 BC. In Mesopotamia, southern Jordan and the Negev desert, water harvesting systems to collect surface water from intensive rainstorms for use during droughts and dry spells, both for agricultural and domestic purposes, were probably developed simultaneously with the introduction of sedentary societies (Oweis *et al*., 2001). In a recent study from India (Agarwal and Narain, 1997) it has been shown that water harvesting dates back three millennia BC. These indigenous coping strategies died out during the 20th century as a result of the modernisation of water management during the hydraulic era of irrigation developments. Interestingly, these coping strategies are reviving in pace with the realisation by local farming communities that governments are not able to provide security from climatic variability.

There is a large untapped potential for improving local risk management to cope with climatic variability in many rural societies in water scarce environments. There is, furthermore, scope to transfer knowledge between countries and continents, e.g. on water harvesting for food production in semi-arid regions between West Asia, India, China and Africa (SIWI, 2001). In dealing with water for food within a climate change scenario this is important. Rainfed agriculture is practised on 80% of the global cropland, while 20% is under irrigated agriculture. In sub-Saharan Africa over 95% is under rainfed agriculture. Strategies to deal with climate change in irrigated agriculture are less evident, and include primarily efficiency improvements and decisions on changes in storage capacity in a scenario of increased variability and/or changes in cumulative water flows.

On the other hand, for rainfed agriculture, a much broader set of coping strategies can be adopted and adapted, often based on the transfer of indigenous knowledge between regions. It is interesting to note also that combining coping strategies such as bridging of dry spells with investments in especially integrated soil nutrient management, can result in substantial system improvements, where not only risks are reduced and economic benefits increased (from stabilised growth of yields), but additionally water productivity is enhanced through the increased amount of biomass output per unit of water (Rockström *et al*., 2001). Overall, this suggests that for risk reduction in rainfed agriculture, in a scenario of climate change, there is at present already a large space for strategic manoeuvring.

4.9 HOW CAN WE PREPARE FOR MORE SEVERE FLOODS?

4.9.1 Structural measures[1]

Flood protection measures can be structural or non-structural. Structural measures include:

- dams
- flood control reservoirs, i.e. constructing reservoirs where the excess flood waters can be stored, and then released as a controlled flow to help alleviate the flood problem by attenuating flood peaks and
- dikes.

4.9.2 Non-Structural measures[1]

Non-structural measures include:

- zoning, i.e. regulation of development in flood hazard areas by allowing only low value infrastructure on the floodplains
- forecasting systems for warning, evacuation, relief and post-flood recovery
- flood insurance, i.e. the division of risks and losses among a higher number of people over a long time period and
- capacity building by improving awareness of the impacts of flooding, an understanding of processes involved and what is implied in flood preparedness.

4.9.3 Forecasting systems[1]

Forecasting systems hold considerable promise for the future. They may be divided into:

- short-term forecasts, e.g. for flash floods, requiring the use of high technology such as radar or remote sensing as the basis for quantitative precipitation, and hence flood, forecasts and triggering flood action plans
- medium-term forecasts, which include the use of seasonal climate forecasts for reservoir operations, advice on agricultural production and, where applicable, information on snow cover and
- long-term forecasts, which need to be developed for designing flood protection systems.

4.10 HOW CAN WE PREPARE FOR MORE SEVERE DROUGHTS?

4.10.1 Traditional and technological approaches[1]

There are both traditional (indigenous) and technological approaches to coping with the risk of drought. Any technological management of drought requires medium (seasonal) to long-term (annual to decadal) climate forecasts and, therefore, the appropriate modelling tools. This information then has to be translated into early warning and reaction chains.

4.10.2 Supply side protection measures[1]

Supply-side drought protection measures include the following:

- Supplies of water should be augmented by exploiting surface water and groundwater in the area. However, intensive groundwater withdrawals for drought management is not a sustainable remedy. It has caused severe land subsistence in many countries, including Mexico, the USA, Japan, China and Thailand.
- Transfers can be made from surface water sources (lakes and rivers) and from groundwater, if socio-economically and environmentally acceptable.
- Storage of water can be increased. Groundwater reservoirs (aquifers) which store water, when available, can be more advantageous than surface water storage, despite the pumping costs, because of the reduction in evaporation losses. However, this classical drought management policy is becoming increasingly difficult to implement because of its consequences on the environment. For example, when a large upland reservoir storage was created in Thailand, allowing regulation of dry season flow in the upper and middle basin to satisfy domestic and irrigation water demand, upstream activity resulted in a serious decline in water quality, particularly in the lower part of the basin area.

4.10.3 Demand side protection measures[1]

In recent years the emphasis in action plans to combat drought has increasingly shifted from supply side management by provision of water resources in required quantities, to effective demand side management for the finite, and scarce, freshwater resource, i.e. seeking 'megalitres of conserved water' rather than 'megalitres of supplied water'. Possible demand-side measures include:

- improved land use practices
- watershed management
- rainwater/runoff harvesting
- re-cycling water (e.g. use of treated municipal waste water for irrigation)
- development of water allocation strategies among competing demands
- reduction of wastage
- improvements in water conservation via reduction of unaccounted water and
- water pricing and subsidies.

4.10.4 Other contingency planning[1]

Drought contingency planning also requires thorough consideration, including:

- restrictions of water use

- rationing schemes
- special water tariffs and
- reduction of low-value uses such as agriculture.

4.11 A SYNTHESIS OF COPING AND ADAPTATION OPTIONS IN WATER RESOURCES[4]

Table 4.4 lists the DWC's adaptation recommendations for water resource managers, organised by impacted sectors and the type of event they are designed for (Appleton *et al*., 2003). Note that there are, indeed, no major changes in coping with climate change and climate variability compared to what is being done (or should be done) in Integrated Water Resources Management already. The determination of the necessity of these measures will vary depending upon whether or not (and to what degree) climate change and variability are taken into account, i.e. the amount of variability and the level of the unexpected event.

4.12 WHEN ADAPTING TO POSSIBLE EFFECTS OF CLIMATE CHANGE ON WATER RESOURCES IN SOUTH AFRICA, WHAT PRIMARY, SECONDARY AND TERTIARY IMPACTS NEED TO BE RESEARCHED?[2]

Primary impacts of climate change on hydrological responses focus solely on changes in total/averaged flows, e.g. MAR.

Secondary impacts still deal with only fluxes of water *per se*, and would include

- changes in the seasonality of streamflows with respect to
  - flow duration curves
  - supply and demand for various sectors, e.g. irrigation or domestic
  - with knock-on effects on water pricing/licensing and
  - effects on water resources infrastructure, including sizing of reservoirs, curtailment rules, or reservoir maintenance
- changes in rainfall and streamflow variability
  - at inter-annual time scales
  - intra-annual time scales
  - including effects on vegetation dynamics and resultant hydrological responses
  - the regional amplification of variability and
  - persistencies of flows above or below selected thresholds
- changes in magnitudes and frequencies of extreme events related to both
  - floods and
  - droughts, including
  - peaks over threshold analyses and
- extreme events from different populations of meteorological flood/drought generating mechanisms
- changes in groundwater recharge or

Table 4.4 The DWC's adaptation recommendations for water resources managers (Appleton *et al*., 2003)

ENHANCE ADAPTIVE CAPACITY	IMPACTED SECTOR(S)	COPING WITH/ ADAPTING TO?
TECHNOLOGICAL AND STRUCTURAL		
-Storage and Reticulation		
-Surface water		
-Large Reservoirs	-BWS; IAG; NWP; RWP; AGI; MUN; DMT; HEP;	-FLF; FLR; DRH; WSS; STS
-Small Reservoirs	-AGI; AGC; AGP; RWP; IHH; PRC; AQE	-FLF; DRA; DRH; WSS
-Groundwater		
-Artificial Recharge	-MUN; BWS; RWP; AQE; DMT; AGI	-DRH; WSG
-Borehole Drilling	-PRC; RWP; IHH; AGP	-DRH; DRA; WSG
-Sand Dams	-MUN; BWS; RWP; AQE	-FLF; DRH; WSS; WSG
-Scavenger/Gallery Wells	-MUN; PRC; BWS; RWP; DMT	-DRH; SLR; WQU; WSG
-System Maintenance		
-Supply Leakage Control	-MUN; BWS	-DRH; WSS; WQU
-Irr. Equip. Maintenance	-AGI	-DRA
-Irrigation Canal Leakage	-AGI	-DRA
-Rainwater Harvesting	-PRC; IHH	-DRH; DRA; WSS; WSG
-Water Re-use/Recycling	-MUN; PRC	-DRH; DRA; WSS
-Desalination	-MUN; BWS	-DRH; WSS
-Flood/Storm Surge Control		
-Structures (i.e. Levees, Dikes, Sand, Duning, Wave Breaks, Planting)	-RWP; MUN; TSP; DMT; AGC; AQE	-FLF; FLR; SLR; STS
-Early Warning Systems		
-Near Real Time (Hours to Days)	-MUN; DMT; IHH	-FLF; FLR
-Short-Term (Days to Weeks)	-MUN; AGI; AGC; AGP; IHH; DMT	-FLR; DRH; DRA
-Medium-Term (Month to Season)	-MUN; AGI; AGC; AGP; IHH; DMT	-DRH; DRA; WSS; WSG
-Long-Term (Years to Decades)	-MUN; RWP; IHH; DMT; AQE; HEP	-DRH; WSS; WSG
-Communicate Forecasts to End-Users	-MUN; IHH; AGI; AGC; AGP; BWS	-FLF; FLR; DRH; DRA; SLR; STS
-Operations/System Improvements		
-Reservoir Operations Rules	-MUN; AGI; DMT; BWS; HEP	-FLF; FLR; DRH
-Retrofitting Existing Structures	-MUN; BWS; DMT	-FLF; FLR; SLR; STS; WSS; WSG
-Irrigation		
-Scheduling	-AGI; AGC	-DRA
-Water Demand Management	-MUN; IHH; RWP; NWP; BWS	-DRA; DRH; SLR; WSS; WSG; WQU
-Indigenous Coping Strategies	-PRC	-FLF; FLR; DRH; SLR; STS; WSS
-Precipitation Enhancement	-AGI; AGC; AGP; AQE; DMT	-DRA
KNOWLEDGE/SKILLS/PARTICIPATION	IMPACTED SECTOR(S)	COPING WITH/ ADAPTING TO?
-Research and Development		
-Efficient Technologies	-ALL	-ALL
-Upgrade Climate Modelling	-ALL	-ALL
-Downscaling	-ALL	-ALL
-Improve Forecast Skill/ Dissemination Network	-BWS; RWP; NWP; AGI; AGC; AGP; MUN; IHH;	-ALL
-Drought Resistent Crops	-AGI; AGC; AGP	-DRA
-Development of Risk Maps/Floodlines	-INS; NWP; DMT; TSP	-FLR; DRH; SLR; STS
-Training and Dissemination		
-Participatory Approach in Decision-Making	-ALL	-ALL
POLICY INSTRUMENTS	IMPACTED SECTOR(S)	COPING WITH/ ADAPTING TO?
-International Conventions	-NWP	-ALL
-International Water Agreements	-NWP; RWP; TSP; DMT	-ALL
-International Trade	-NWP; MUN; AGI; AGC; DMT	-DRA
-National Water Master Plans	-NWP; RWP; DMT	-ALL
-Disaster Management Policies	-NWP; RWP; MUN; IHH; DMT	-ALL
RISK SHARING/SPREADING	IMPACTED SECTOR(S)	COPING WITH/ ADAPTING TO?
-Private Sector Strategies		
-Insurance		
-Primary Insurers	-IHH; AGI; DMT; TSP	-DRA; DRH; FLR; FLF
-Re-Insurance	-MUN; DMT; TSP	-FLR; FLF
-Micro-Insurance	-AGI; AGC; AGP; DMT; IHH; PRC	-FLF; FLR; DRA
-Banks		
-Development	-NWP; DMT	-ALL
-Private	-IHH; DMT	-DRA; FLR; FLF
-Micro-Lenders	-AGI; AGC; AGP; IHH; DMT; PRC	-DRA; FLF; FLR
CHANGE OF USE/ACTIVITY/LOCATION	IMPACTED SECTOR(S)	COPING WITH/ADAPTING TO?
-Land Use Measures		
-Conservation Structures	-MUN; AGI; AGC; AQE	-FLF; FLR; SLR; STS; DRA
-Adaptive Spatial Planning	-MUN; RWP; AGI; AGC; AGP; TSP; DMT	-FLF; FLR; SLR; STS
-Tillage Practices	-AGI; AGC	-DRA
-Crop Change	-AGI; AGC	-DRA
-Resettlement	-IHH; PRC	-FLR; DRH; SLR; WQU

Key to abbreviations:

Impacted Sectors:		Coping with/adapting to:	
NATIONAL WATER PLANNERS	NWP	FLOODS: FLASH	FLF
REGIONAL WATER PLANNERS	RWP	FLOODS: REGIONAL	FLR
MUNICIPALITIES	MUN	DROUGHT: AGRICULTURAL	DRA
BULK WATER SUPPLIERS	BWS	DROUGHT: HYDROLOGICAL	DRH
INDIVIDUAL HOUSEHOLDS	IHH	WATER SUPPLY: SURFACE	WSS
POOR RURAL COMMUNITIES	PRC	WATER SUPPLY: GROUNDWATER	WSG
AGRICULTURE: IRRIGATED	AGI	WATER QUALITY	WQU
AGRICULTURE: CROPPING	AGC	STORM SURGES	STS
AGRICULTURE: PASTORAL	AGP	SEA LEVEL RISE	SLR
DISASTER MANAGEMENT	DMT		
HYDRO-ELECTRIC POWER	HEP		
THERMAL ELECTRIC POWER	TEP		
TRANSPORT	TSP		
INSURANCE	INS		

- effects of land use on water availability, mainly through alterations in the partitioning of rainfall into stormflow and baseflow.

Tertiary (higher order) impacts of climate change go beyond fluxes of water *per se* to include

- changes in water quality, for example of
  - sediment yield
  - water chemistry (N and P; salinity)
  - biological status of water (*E. coli*)
  - water temperature (water-borne diseases)
- and consequences thereof on
  - purification costs or
  - human health
- changes in aquatic ecosystems and effects of climate change on
  - ecosystem goods and services or
  - instream flow requirements

and including questions on whether or not habitats should adapt to the changed climatic regimes or be "protected" to remain in equilibrium with the present climatic regime.

Furthermore, climate perturbations, through the hydrological system, may result in

- changes in the potential for conflict over shared rivers
  - where rivers form international boundaries, or especially
  - where rivers discharge downstream from one country to another

  as well as
- changes in water issues to the poor, who often live either
  - on floodplains, which may become more prone to flooding in future, or alternatively live
  - along watersheds, where streams which are ephemeral now already may become even more so in future.

5 MODELLING EXERCISES ON IMPACTS OF CLIMATE CHANGE ON HYDROLOGICAL PROCESSES AND WATER RESOURCES

5.1 WHAT ARE THE NECESSARY ATTRIBUTES OF A HYDROLOGICAL MODEL USED TO SIMULATE POTENTIAL IMPACTS OF CLIMATE CHANGE?[6]

Such a model needs to be

- ***conceptual*** in that it conceives of a one, two or even three dimensional system in which important processes and couplings are idealised, and
- ***physical*** to the degree that the physical processes are represented explicitly through observable variables.

The model should, at minimum, be functional (i.e. threshold based) in its process representation, although not necessarily always in a purely mechanistic (i.e. rate based) way (Schulze, 1998).

Hydrological processes of relevance which take place on a catchment subjected to climate variability, climate change and to anthropogenic pressures, and for which a conceptual-physical model is necessary, are those

- involving interactions of exchanges of water vapour, CO_2 and energy (condensation, precipitation, runoff, evaporation and transpiration together with its CO_2 driven feedbacks),

modified by characteristics of

- soil (surface infiltrability, subsurface transmissivity/redistribution of soil water and water holding capacity),
- land cover and use (above-ground attributes related to biomass and its seasonal distribution, physiology and structure; surface attributes of soil protection by litter/mulch or of tillage practices, or impervious vs pervious surfaces; and below-ground attributes relating to root structure and distribution), and
- topographic features of the landscape (altitude, slope, aspect, toposequence and topographic position in the landscape).

A conceptual-physical model's structure, which includes physically realistic initial and boundary conditions, needs to furthermore reproduce hydrological responses associated with

- changes in land use and management practices
- changes in atmospheric CO_2 concentrations and
- changes in individual event, intra-seasonal and inter-seasonal climate, particularly of rainfall characteristics and especially of extreme events.

The model should reproduce non-linear and scale-related catchment responses explicitly, where these are 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)
  - continuity (e.g. groundwater movement) and
  - delayed responses (e.g. baseflow)
- thresholds required for processes to commence, e.g.
  - for surface runoff : when rainfall intensity exceeds infiltrability of the soil, or when saturated overland flow occurs from the upslope accumulations saturating a variable source area around channels; or
  - for subsurface flow : by considering soil horizonation and toposequence when determining interflow, as well as considering when and whether the groundwater table is ‘connected’ to the channel when baseflows are determined

Furthermore, the model should be able to account for

- dominant processes changing with scale, including
- identification of emerging properties, i.e. those arising from the mutual interaction of small scale properties among themselves, such as edge effects of advection leading to enhanced evaporation around irrigated fields, and
- representing disturbance regimes, e.g. drainage of fields, gradual changes in land use intensification over time (as in agriculture and urbanisation), or in extensification (as in overgrazing impacts), or abrupt changes resulting from fires or flooding.

While no type of model is totally devoid of some parameter adjustment, conceptual-physical models should, in theory, not require external calibration procedures to produce robustly acceptable results.

A major advantage of such models is that, because of their high level of conceptualisation and physically based boundary conditions, they may be used with confidence in extrapolations involving ‘what-if’ scenarios of hitherto unmeasured land management, extreme event or climate variability change, beyond what has been observed on a given catchment. Such extrapolation cannot be undertaken with the same assurance with externally calibrated models because of the equifinality of parameter sets and their dependence on the state of the catchment during the calibration period (Beven, 2000).

In order to model climate change (and other) impacts the model should, ideally, operate on a daily time step. Reasons include the following:

- The day, and diurnality, is a *universal natural time step* (which neither the second, minute, hour, week or month are). The next natural time step up would be the season, and that displays no universality.
- Diurnality encapsulates, albeit not perfectly, many hydrologically related processes (e.g. evaporation, transpiration and many discrete rainfall events).
- Furthermore, many operational decisions are made according to daily conditions (e.g. irrigation, tillage, reservoir operations).
- There are, however, two other major reasons for promoting daily time step modelling. The first is the availability of data:
  - South Africa, for example, has daily rainfall records of over 20 years' duration for nearly 4 000, and for over 40 years' duration for over 1800 stations (Figure 2.3), while for the same durations autographically recorded data for time steps < 1 day are available for only 97 and 8 stations respectively (Smithers and Schulze, 2000a; 2000b).
  - Similarly, daily values of maximum and minimum temperatures in South Africa are available historically for over 900 stations and for pan evaporation from over 400 stations.
  - The station networks with daily data are, thus, relatively dense (although not in all hydrologically critical areas) and have records of relatively long duration.
  - Furthermore, for climate change studies daily values are now becoming available for present (1961-90) and CO_2 enhanced (2041-70) scenarios from the HadCM3 GCM.
- Secondly, daily time step models provide a vast array of potential and realistic and, in the context of South Africa's National Water Act and IWRM, highly relevant output which (say) monthly models do not, e.g. on
  - modes of irrigation scheduling
  - peak discharge
  - event based sediment yields
  - phosphorous/nitrate yields
  - near real-time catchment states
  - impacts on land management
  - climate change impacts with CO_2 transpiration feedbacks
  - reservoir operations
  - instream flow requirements
  - wetlands functions
  - flow routing through channels/reservoirs
  - reservoir status
  - crop yields (dryland and irrigated) or
  - explicit generation of stormflow, interflow and baseflow

5.2 USING THE *ACRU* AGROHYDROLOGICAL MODELLING SYSTEM FOR MODELLING CLIMATE CHANGE IMPACTS ON HYDROLOGICAL RESPONSES AND WATER RESOURCES[6]

The *ACRU* agrohydrological modelling system (Schulze, 1995) complies with many of the attributes outlined above. It has the following characteristics:

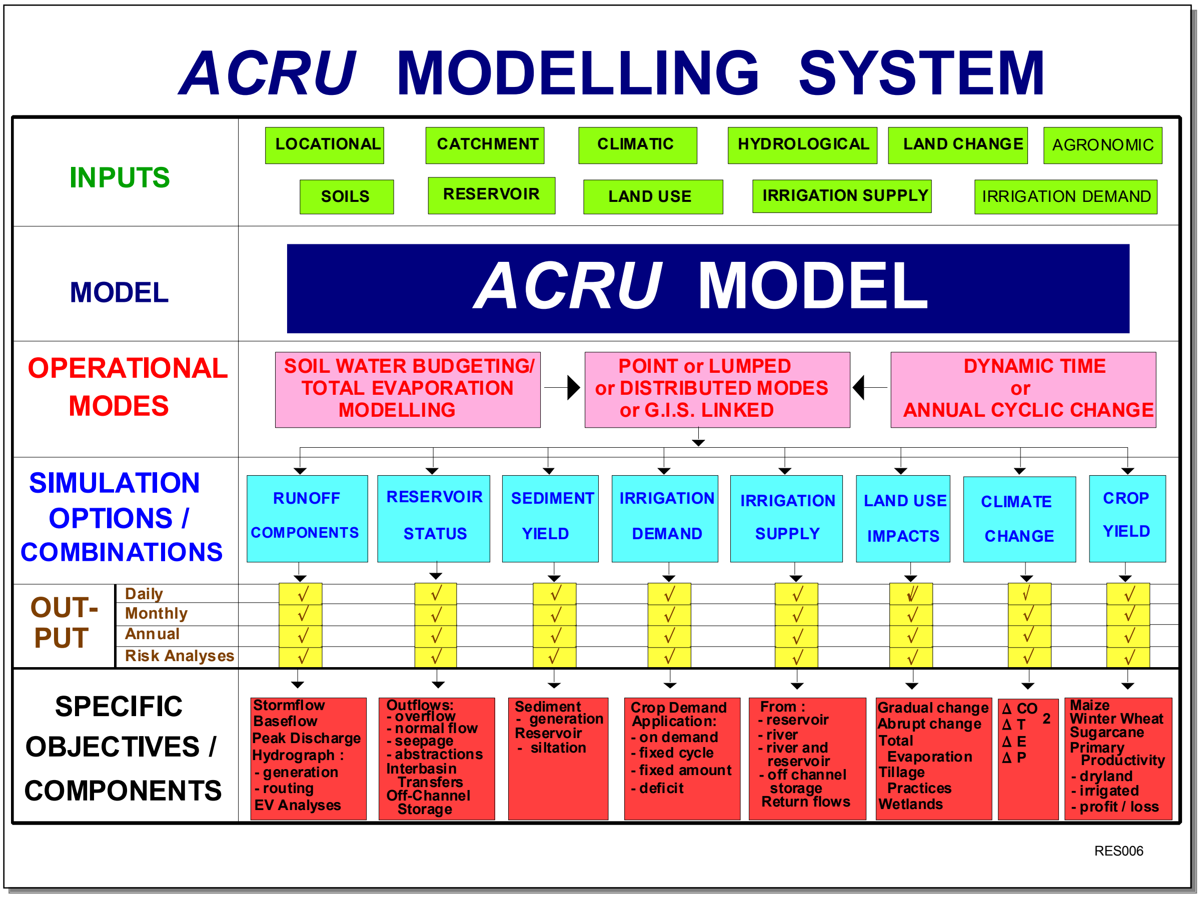


Figure 5.1 The *ACRU* agrohydrological modelling system: Concepts (after Schulze, 1995)

- It is a *physical conceptual* model, i.e. it is conceptual in that it conceives of a system in which important processes and couplings are idealised, and physical to the degree that physical processes are represented explicitly.
- *ACRU* is not a parameter fitting or optimising model. Variables (rather than optimised parameters values) are, as a rule, estimated from physically based characteristics of the catchment.
- It is a *multi-purpose* model (Figure 5.1) which integrates the various water budgeting and runoff production components of the terrestrial hydrological system. It can be applied as a versatile model for design hydrology, crop yield modelling, reservoir yield simulation, ecological requirements, irrigation water demand/supply, water resources assessment, planning optimum water resource utilisation/allocation, conflict management in water resources, climate change impacts and land use impacts - in each case with associated risk analyses.
- The model uses *daily time steps* and thus daily climate input data, thereby making optimal use of available data. Certain more cyclic, conservative and less sensitive variables, (e.g. temperature, reference potential evaporation), for which values may have to be input at monthly level (if daily values are not available) are transformed internally in *ACRU* to daily values by Fourier Analysis. More sensitive intra-daily

information (e.g. of rainfall distribution) is obtained by synthetic disaggregation of daily values into shorter duration time steps within the model.

- The *ACRU* model revolves around daily *multi-layer soil water budgeting* and the model has been developed essentially into a versatile total evaporation model (Figure 5.2). It has, therefore, been structured to be highly sensitive to climate and to land cover, land use and management changes on the soil water and runoff regimes, and its water budget is responsive to supplementary watering by irrigation, to changes in tillage practices, enhanced atmospheric CO_2 concentrations or to the onset and degree of plant stress.
- *ACRU* has been designed as a *multi-level* model, with either multiple options or alternative pathways (or a hierarchy of pathways) available in many of its routines, depending on the level of input data available, or the detail of output required. Thus, for example, reference potential evaporation, interception losses, values of soil water retention constants, maximum (i.e. 'potential') as well as total evaporation ('actual evapotranspiration'), leaf area index, components of peak discharge estimation, hydrograph routing, reservoir storage : area relationships or the length of phenological periods in crop growth, may all be estimated by different methods according to the level of input data at hand or the relative accuracy of simulation required.

ACRU Agrohydrological Model

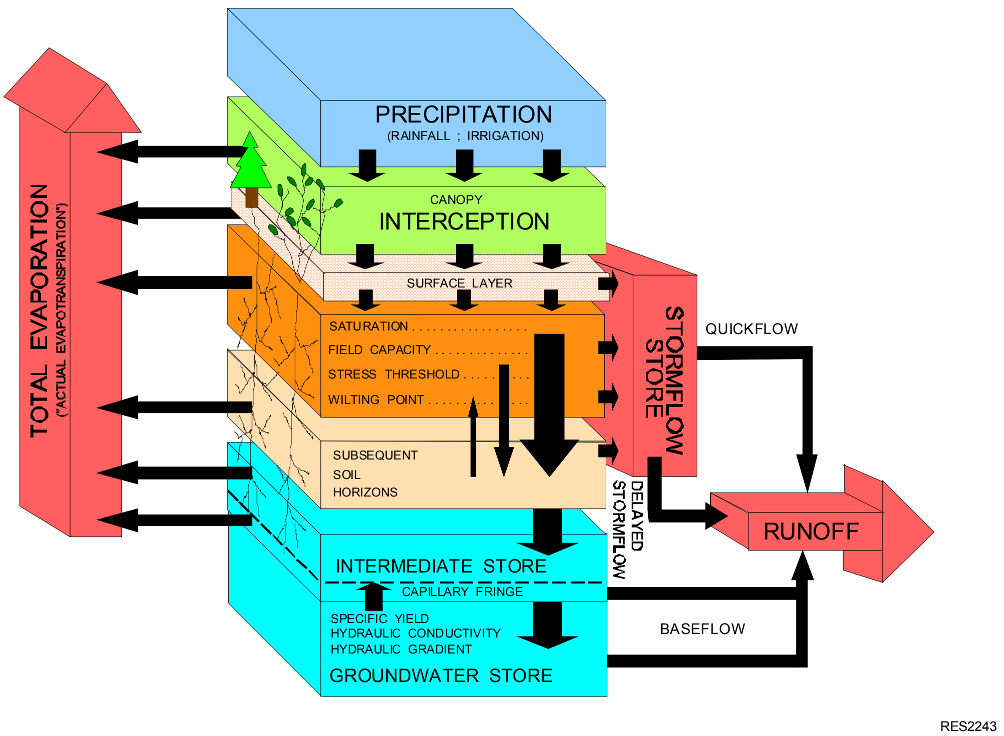


Figure 5.2 The *ACRU* agrohydrological modelling system: General structure (after Schulze, 1995)

- *ACRU* can operate as a *point* model, as a *lumped* small catchments model, on large catchments or at national scale. In areas of complex land uses and soils, over large catchments or at national scale *ACRU* operates as a *distributed* cell-type model. In distributed mode individual subcatchments which ideally should not exceed 50 km^2, but which are often at the level of Quaternary or sub-Quaternary (Quinery) Catchments in South Africa, are identified. Once discretised into subcatchments, flows can take place from 'exterior' through 'interior' cells according to a predetermined scheme, with each subcatchment able to generate individually requested outputs which may be different to those of other subcatchments or with different levels of input/information.
- The model includes a *dynamic input option* to facilitate modelling the hydrological response to climate or land use or management changes in a time series, be they long term/gradual changes (e.g. forest growth, urbanisation, expansion of an irrigation project or climate trends), or abrupt changes (e.g. clearfelling, fire impacts, construction of a dam, development of an irrigation project, or introduction of new land management strategies such as tillage practices), or changes of an intra-annual nature (e.g. crops with non-annual cycles, such as sugarcane). A dynamic input file is then accessed each year, with the new variable inputs to be used from that year onwards, e.g. water use coefficients, root mass distributions, planting dates or soils properties (e.g. for new tillage practices).
- *ACRU* operates in conjunction with the interactive *ACRU Menubuilder* and *Outputbuilder* and the associated *ACRU Input Utilities*. The latter are suites of software programs to aid in the preparation of input data and information. The *ACRU Menubuilder* prompts the user with unambiguous questions, leading the user into inputing, for example, complex distributed catchment information easily. The *Menubuilder* contains alternative decision paths with preprogrammed *Decision Support* values. Furthermore, the *Menubuilder* includes a *HELP* facility, built-in *default values* as well as warning and error messages. The *Outbuilder* allows the user to select, from a predefined list, which variables are to be stored during a simulation for subsequent output and analysis.
- The *ACRU Output Utilities* enable the user to print out, and to analyse, any observed as well as simulated results. The types of analyses include frequency analysis, extreme value analysis and comparative statistics in order to determine the goodness of fit between simulated and observed data.

5.3 APPLICATION OF THE *ACRU* MODEL TO SIMULATE IMPACTS OF CLIMATE CHANGE: A CASE STUDY EXAMPLE FROM THE UPPER MGENI CATCHMENT, SOUTH AFRICA

5.3.1 Background and Questions[7]

In the 1 and 2 day training courses the model would have been configured for this particular catchment with respect to a daily rainfall file, typical soils, characteristics etc and the application would be demonstrated by staff trained in *ACRU* model applications. In the 2-3 week module a short course on the *ACRU* is given as part of the package.

Given below is a typical set of questions on impacts of climate change on a small catchment of 5.17 km^2 in the Upper Mgeni Catchment at 29°43'S, 30°15'E, 1 150 m altitude.

1. For the Upper Mgeni catchment, obtain the Had2CM(excl. Sulphates) climate change parameters for a $X2CO_2$ scenario
   - ΔP for each month
   - ΔT_{mx}, ΔT_{mn} for each month
   - For ΔE_r, use the Linacre (1991) monthly equation (Why?)

EXERCISE A : PROCESS STUDIES

2. Set up a base *ACRU* run for the 5.17 km^2 Upper Mgeni catchment, using the present climate data file for a 3 year run, 1990 - 1992.

   However,
   - land use is maize (planted 1 November, 140 day growing season, LCOVER = . .)
   - EVTR = 2 (Why?)
   - CO_2 influences switched off
   - Soils characteristics as given
   - Irrigation: Set up for maize (as above) for 50 ha, irrigation from reservoir
   - Reservoir : 80 000 m^3, 200 m wide, default ARCAP

3. Obtain a daily printout for the middle year, October-September, showing, *inter alia*,
   - transpiration (topsoil/subsoil)
   - soil water evaporation (topsoil)
   - soil moisture content (topsoil/subsoil)
   - crop coefficient
   - runoff (stormflow/baseflow)
   - overflow and water content (%) of dam
   - irrigation water demand
   - reference potential evaporation.

4. Rerun the above, but switch on X2 CO_2 for a C4 plant.
   Plot comparisons of the above variables.
   Comment on your results.

5. Rerun for climate change influences, i.e.
   Change T_{mx}, T_{mm}, P. Do not yet switch on X2 CO_2.
   Compare answers with Run 3.

6. Now switch on X2 CO_2 for a C4 plant.
   Compare answers with those of Run 5.

7. Rerun No 6 for a X2 CO_2 scenario, but make your soil a cracking soil (clay > 50%). Comment on the hydrological responses.
8. Do a run where you use the base P, no X2 CO_2 but change T_{mx}, T_{mm}. Compare with Run 3.

EXERCISE B: WATER RESOURCES IMPACT STUDIES

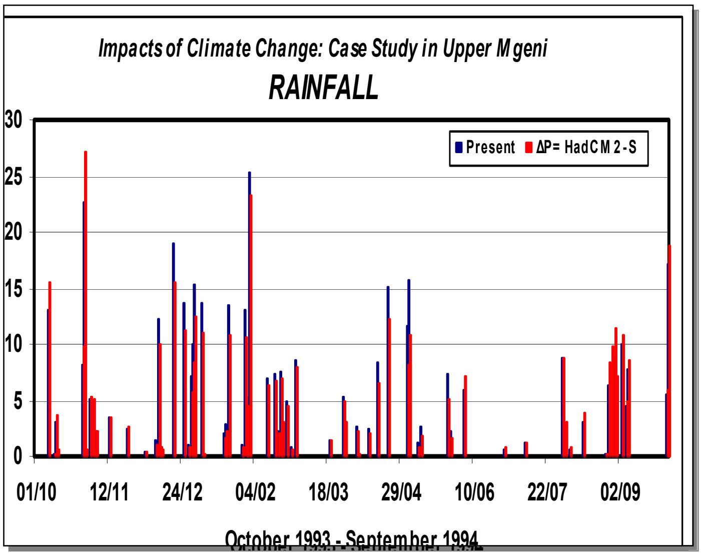
9. Reset the entire Upper Mgeni catchment for a base run for present land use conditions, using EVTR = 2 (Why). Do a run for present climatic conditions for all years of record, printing out frequency analyses for stormflow, baseflow, total flow and if relevant, reservoir yield (DAMPER, OVERFL) at the outlet of the catchment.

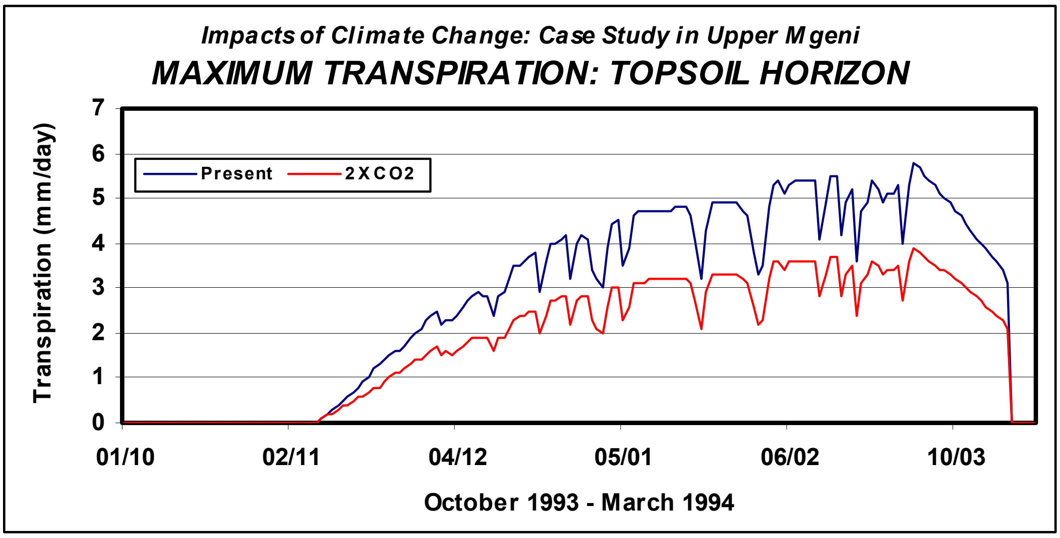
10. Rerun No 9 but with ΔP, ΔT_{tmx}, ΔT_{mm}, ΔCO_2 (C4 pathway) and compare results with those of Run 9. Discuss the potential impacts of the climate change scenario on the water resources, incl. changes in flow amounts, seasonality of flows and the partitioning of streamflow.

11. These results must become part of your climate change impacts modelling report.

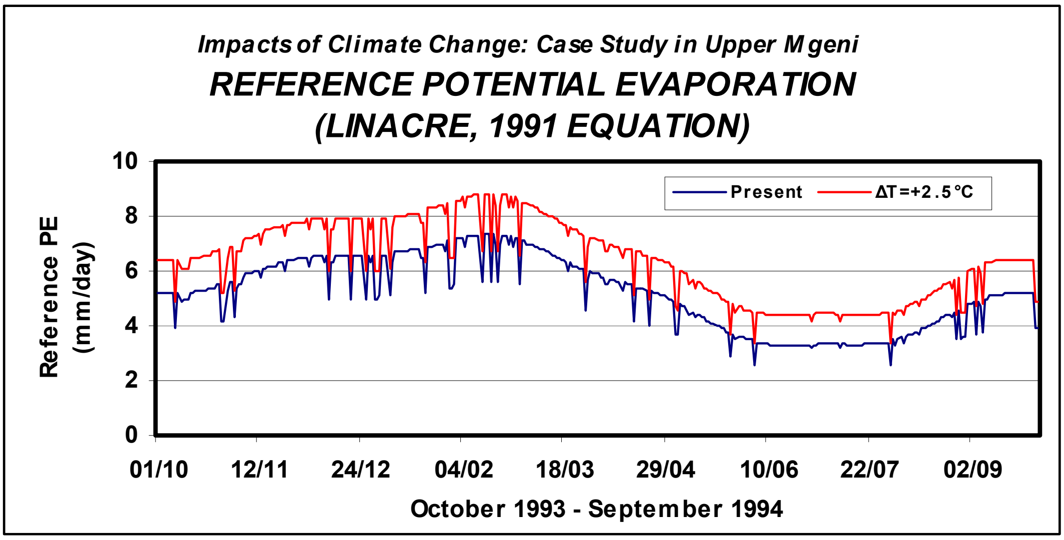
5.3.2 Selected results[7]

Given below, as a series of diagrams, are selected results from the above modelling exercise. These results would then be interpreted, and the differences explained, in light of process representations of climate change impacts in the *ACRU* model, the particular climate change scenario used (in this example the HadCM2-S GCM for x2 CO_2 conditions), and the questions posed above.

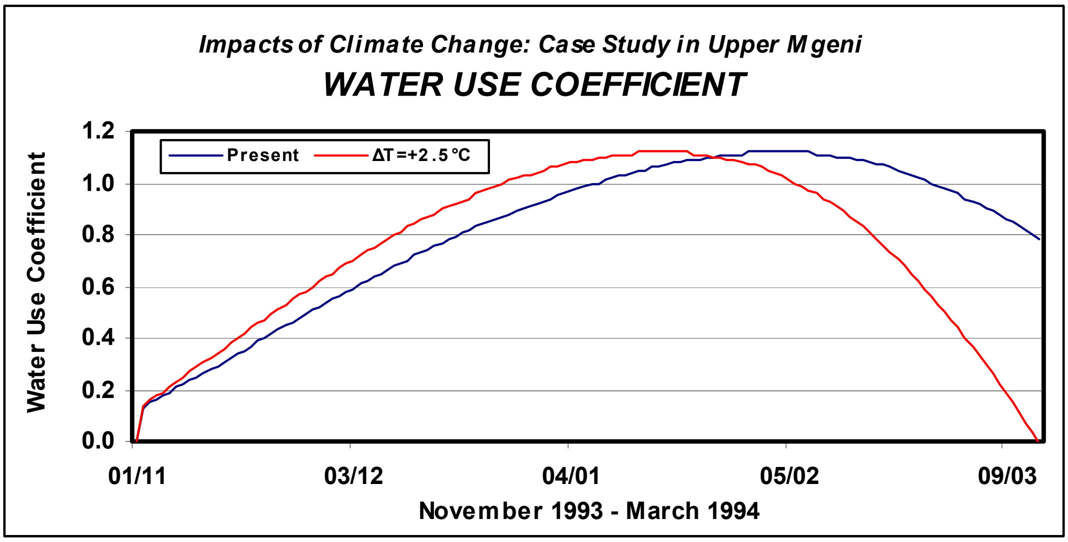




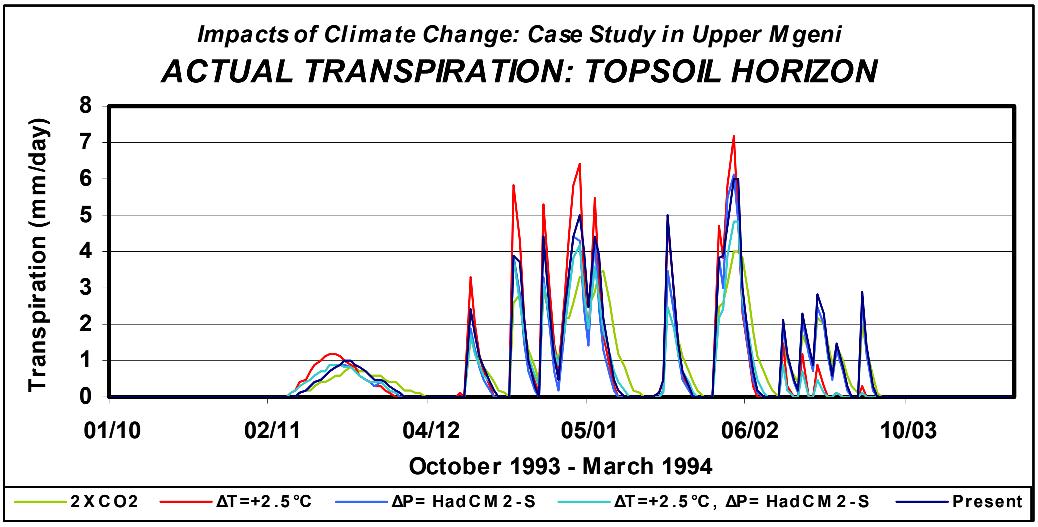
Impacts of Climate Change: Case Study in Upper Mgeni
MAXIMUM TRANSPIRATION: TOPSOIL HORIZON
Transpiration (mm/day)
7
6
5
4
3
2
1
0
Present
2 X CO2
01/10
02/11
04/12
05/01
06/02
10/03
October 1993 - March 1994

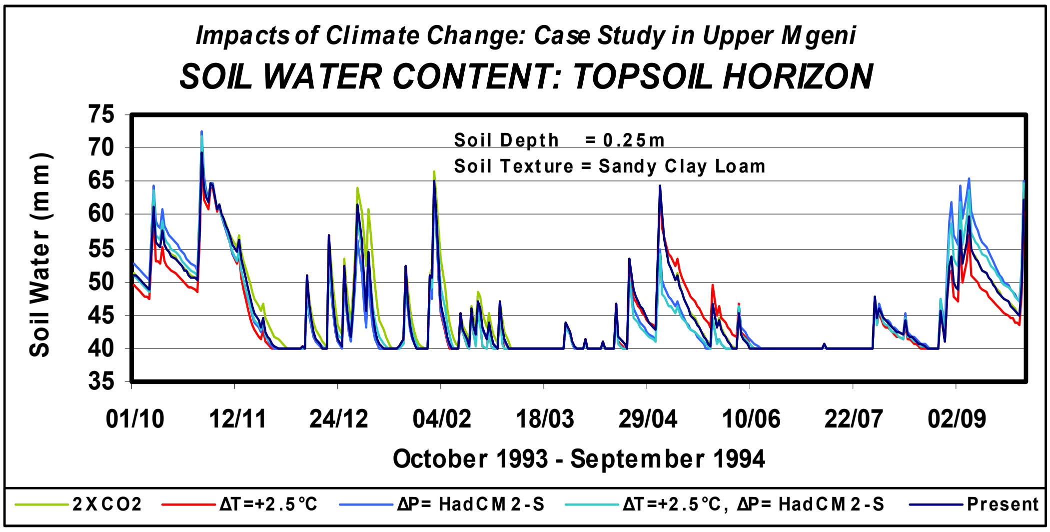


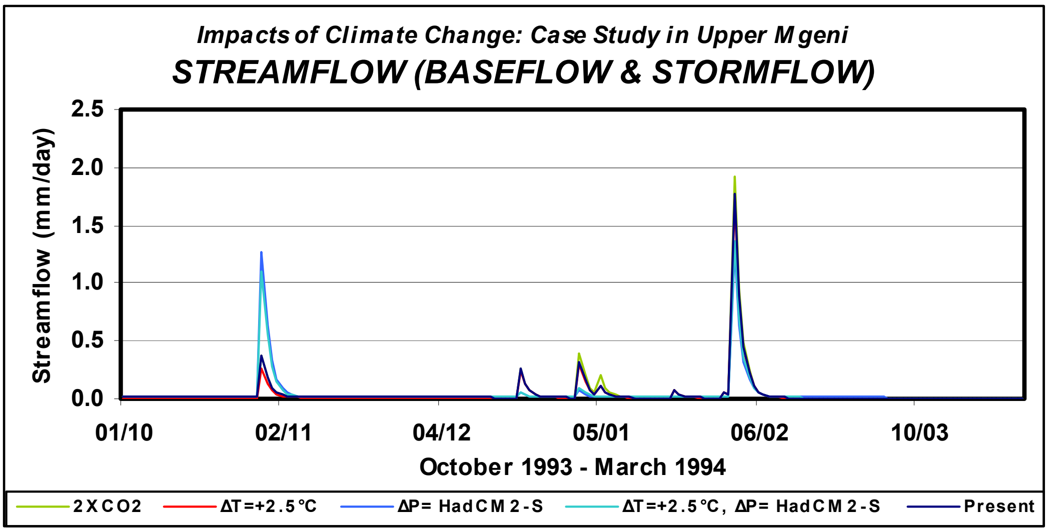
Impacts of Climate Change: Case Study in Upper Mgeni
REFERENCE POTENTIAL EVAPORATION
(LINACRE, 1991 EQUATION)
Reference PE (mm/day)
10
8
6
4
2
0
Present
ΔT=+2.5°C
01/10
12/11
24/12
04/02
18/03
29/04
10/06
22/07
02/09
October 1993 - September 1994

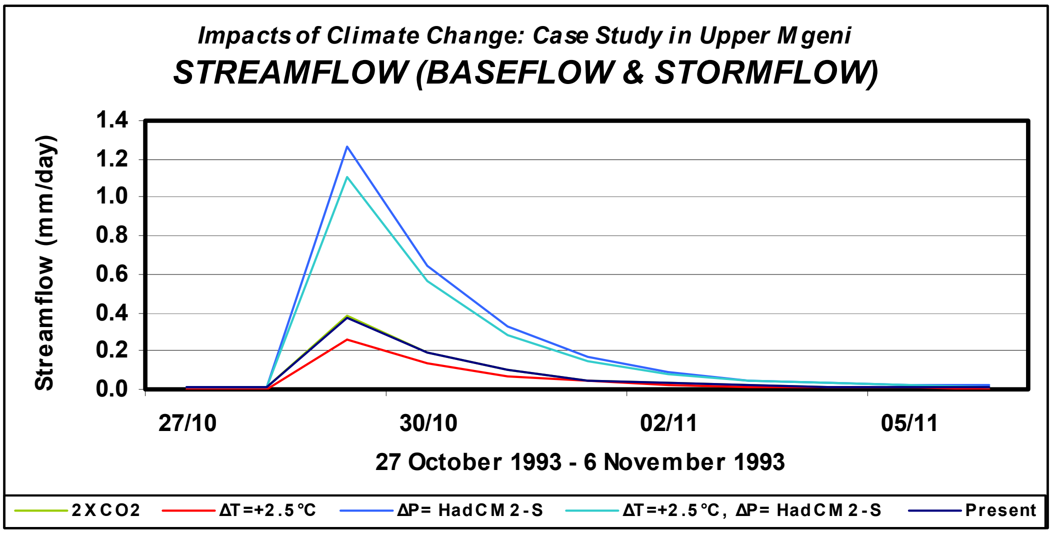


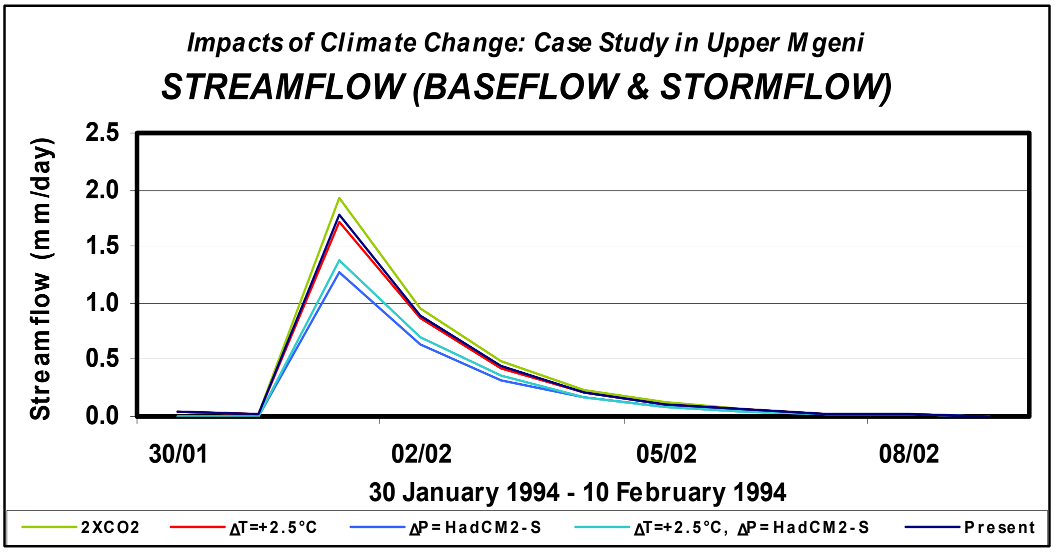
Impacts of Climate Change: Case Study in Upper Mgeni
WATER USE COEFFICIENT
Water Use Coefficient
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Present
ΔT=+2.5°C
01/11
03/12
04/01
05/02
09/03
November 1993 - March 1994

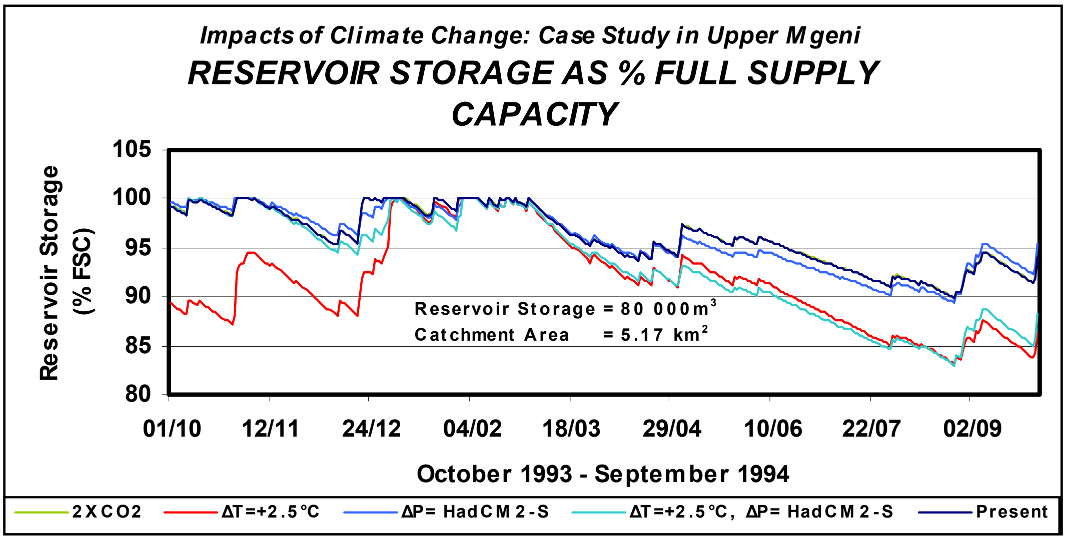

Impacts of Climate Change: Case Study in Upper Mgeni
ACTUAL TRANSPIRATION: TOPSOIL HORIZON
Transpiration (mm/day)
0
1
2
3
4
5
6
7
8
01/10
02/11
04/12
05/01
06/02
10/03
October 1993 - March 1994
2XCO2
ΔT=+2.5°C
ΔP= HadCM2-S
ΔT=+2.5°C, ΔP= HadCM2-S
Present

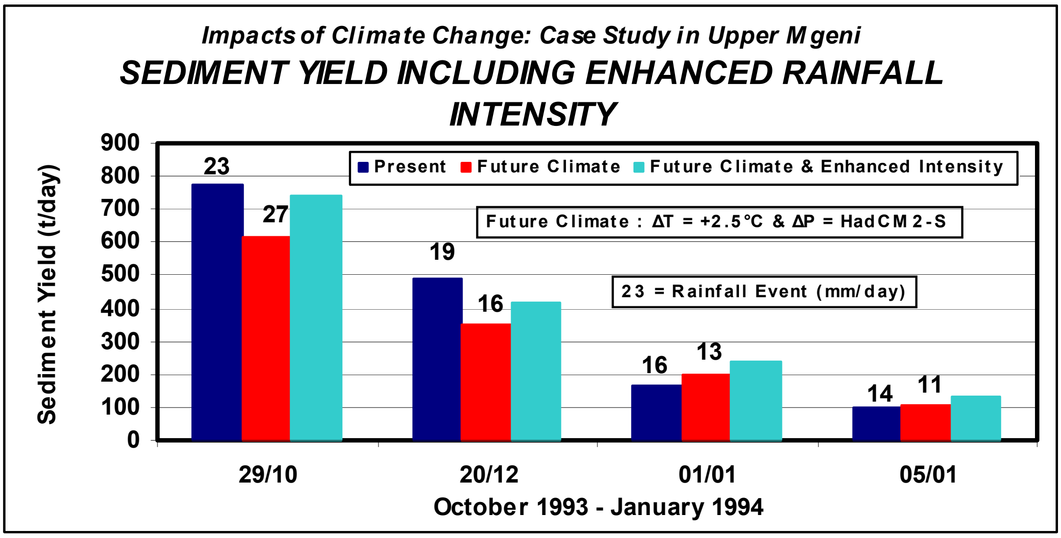

Impacts of Climate Change: Case Study in Upper Mgeni
SOIL WATER CONTENT: TOPSOIL HORIZON
Soil Depth = 0.25m
Soil Texture = Sandy Clay Loam
Soil Water (mm)
35
40
45
50
55
60
65
70
75
01/10
12/11
24/12
04/02
18/03
29/04
10/06
22/07
02/09
October 1993 - September 1994
2XCO2
ΔT=+2.5°C
ΔP= HadCM2-S
ΔT=+2.5°C, ΔP= HadCM2-S
Present


Impacts of Climate Change: Case Study in Upper Mgeni
STREAMFLOW (BASEFLOW & STORMFLOW)
Streamflow (mm/day)
0.0
0.5
1.0
1.5
2.0
2.5
01/10
02/11
04/12
05/01
06/02
10/03
October 1993 - March 1994
2XCO2
ΔT=+2.5°C
ΔP= HadCM2-S
ΔT=+2.5°C, ΔP= HadCM2-S
Present


Impacts of Climate Change: Case Study in Upper Mgeni
STREAMFLOW (BASEFLOW & STORMFLOW)
Streamflow (mm/day)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
27/10
30/10
02/11
05/11
27 October 1993 - 6 November 1993
2XCO2
ΔT=+2.5°C
ΔP= HadCM2-S
ΔT=+2.5°C, ΔP= HadCM2-S
Present


Impacts of Climate Change: Case Study in Upper Mgeni
STREAMFLOW (BASEFLOW & STORMFLOW)
Streamflow (mm/day)
2.5
2.0
1.5
1.0
0.5
0.0
30/01
02/02
05/02
08/02
30 January 1994 - 10 February 1994
2XCO2
ΔT=+2.5°C
ΔP=HadCM2-S
ΔT=+2.5°C, ΔP=HadCM2-S
Present


Impacts of Climate Change: Case Study in Upper Mgeni
RESERVOIR STORAGE AS % FULL SUPPLY CAPACITY
Reservoir Storage (% FSC)
105
100
95
90
85
80
Reservoir Storage = 80 000m³
Catchment Area = 5.17 km²
01/10
12/11
24/12
04/02
18/03
29/04
10/06
22/07
02/09
October 1993 - September 1994
2XCO2
ΔT=+2.5°C
ΔP= HadCM2-S
ΔT=+2.5°C, ΔP= HadCM2-S
Present



5.3.3 Access to the *ACRU* model and its documentation[7]

The *ACRU* model homepage is at www.beeh.unp.ac.za/acru. Once in the homepage, both software and comprehensive documentation may be accessed. The main documentation on *ACRU* consists of the following:

- Schulze, R.E. 1995. *Hydrology and Agrohydrology: A Text to Accompany the ACRU 3.00 Agrohydrological Modelling System.* Water Research Commission, Pretoria, South Africa, Report TT69/95. pp552.
- Smithers, J.C. and Schulze, R.E. 1995. *ACRU Agrohydrological Modelling System: User Manual Version 3.00.* Water Research Commission, Pretoria, South Africa, Report TT70/95. pp 368.
- Schulze, R.E. and Smithers, J.C. 2003. The *ACRU* Modelling System as of 2001: Background, Concepts, Structure, Output, Typical Applications and Operations. *In*: Schulze, R.E. (Ed) *Modelling as a Tool in Integrated Water Resources Management: Conceptual Issues and Case Study Applications.* Water Research Commission, Pretoria, South Africa, WRC Report 749/1/02. Chapter 2, 47-84. (Also at www.beeh.unp.ac.za, main author's homepage under "downloadable documents").