Please cite as:

Schulze, R.E. 2008. Integrated Water Resources Management as a Medium for Adapting to Climate Change. *In*: Petermann, T. (Ed) *Towards Climate Change Adaptation - Building Adaptive Capacity in Managing African Transboundary River Basins*. InWent, Zschortau, Germany. Chapter 2, 41-74. ISBN 978-3-939394-28-0.

Chapter 2

Integrated Water Resources Management as a Medium for Adapting to Climate Change

Conceptual, scaling, impacts modelling and adaptation issues within a southern african context

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1. Introduction

> One of the plethora of definitions of Integrated Water Resource Management (IWRM) which abound in the literature is that
>
> IWRM is a philosophy, a process and a management strategy to achieve sustainable use of resources by all stakeholders at catchment, regional, national and international levels, while maintaining the characteristics and integrity of water resources at the catchment scale within agreed limits (DWAF, 1998).

If this South African definition is adopted in this paper, then it may be argued both implicitly and explicitly that IWRM should be a sound medium by which to effect adaptation strategies to impacts of an uncertain future on the water sector under conditions of climate change, and this across a range of spatial and temporal scales.

This paper therefore sets out to discuss issues of getting to grips with some realities and practicalities of IWRM in a context of southern Africa and of climate change (CC) by first asking who water managers are and what they manage, in light of some major paradigm shifts which have taken place in water resource management since the early 1990s. Thereafter, differences in IWRM which exist between more developed and lesser developed countries are highlighted, followed by brief explanations on how the interrelationships between climate change and the hydrological cycle operate, and why the hydrological cycle tends to amplify changes in climate. These sections are followed by one on scale issues and the challenges these present in climate change studies, including some general statements on scales at which operational decisions are made in the water sector, on complexities of spatial and of temporal scales in adapting to climate change within a framework of IWRM and how the spatial scale dilemma in climate change studies has been addressed in South Africa to harmonise with other modelling initiatives in IWRM. Simulation modelling is the primary tool used to assess impacts of CC on hydrological responses, therefore, the next section, on impacts modeling, is prefaced by enquiring into the significance of the water sector in CC studies, followed by a discussion on model requirements for effective climate change impact studies and why the ACRU system is used as the preferred hydrological simulation model in southern African CC impacts studies. The final major section of the paper relates to selected issues on adaptation to CC in the water sector, with emphasis on experiences in South Africa. Adaptation is first placed within a policy framework, both at an overarching national level and then more specifically within the water sector. Among the challenges facing adaptation to CC are, on the one hand, the many uncertainties which remain and on the other, putting into practice the many excellent thoughts which have already emanated from the water sector itself in regard to IWRM, including the role of groundwater, design hydrology, policy/legislation, monitoring and the inter-linkages with the agricultural sector. A framework for adaptation to CC is presented for South Africa, but limits to adaptation are also highlighted. The paper concludes by emphasising that barriers to IWRM, particularly those more frequently evident in developing countries, should not become barriers to climate change adaptation in those countries.

2. Getting to grips with the realities and practicalities of IWRM within the context of climate change

In regard to some realities and practicalities of IWRM within the wider contexts of southern Africa (and Africa as a whole) and of climate change, three issues are addressed, viz. who water managers are, what paradigm shifts they have had to contend with over the past two decades and what differences exist in managing water resources between lesser developed and developed countries.

2.1 Who are water managers and what do they manage?

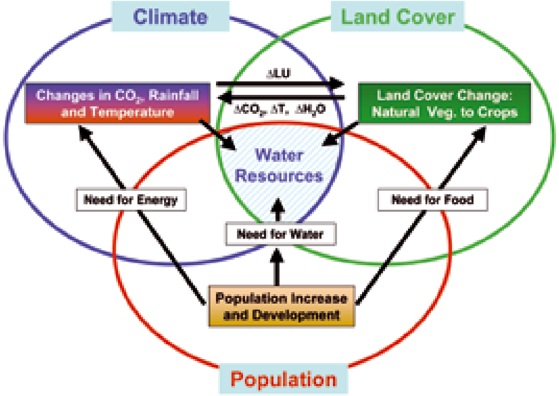


Figure 2.1: The climate - land cover - water resources cycle Schulze, 2007; Idea: Harding & Kabat, 2007

For the professional water resources manager the management of water involves the regulation, control, allocation, distribution and efficient use of existing supplies of water under present and future conditions. This includes management responsibilities towards off-stream users such as irrigators, thermal power plant operators (cooling), municipalities and the industrial sector, as well as towards the development of new water supplies, the control of floods and the provision of water for in-stream uses such as navigation, hydro-electric power, recreation and environmental flows (Figure 2.1).

From a non-professional water management perspective, all levels of government, as well as the private sector and individual stakeholders are routinely engaged in the management of water, be it directly or indirectly. Hence, technically, every individual who uses water is in a manner of speaking a water manager, from the water resource professional to the woman in the village who draws water from a spring or river. Water managers certainly include agriculturalists, both the large-scale commercial farmers who use mostly technical water related systems, and the small-scale subsistence farmers with their rainfed agriculture. Addressing the adaptation options which farmers in the lesser developed countries have is particularly critical, owing to the direct impacts climate variability and change could have on their livelihoods. Nevertheless, water managers are typically considered to be people who are formally trained and involved in some institutionally organised component of water development, delivery/regulation, and who have responsibility and accountability for the decisions that are made (Appleton et al., 2003).

Water managers have to deal with a host of interlinked and integrated issues (Figure 2.2), not only in regard to supply, quality and distribution of water, but also with resource vulnerability and reliability, sustainable water use, biological diversity, ecological integrity with respect to water under both present and future conditions and, in Africa, with issues of equity of water allocation and the Millennium Development Goals.

For many water managers in developing countries, vulnerability to future climate changes may seem to be a far-distant problem. Certainly many would argue for focusing on currently more pressing issues related to population growth, economic underdevelopment, HIV/AIDS 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 into account climate change does not necessarily imply adding any new "magic strategies" to their present practices for coping with climate extremes. What they do have to recognise, however, is that climate variability may be increasing and that future weather for many regions is projected to be more extreme more frequently.

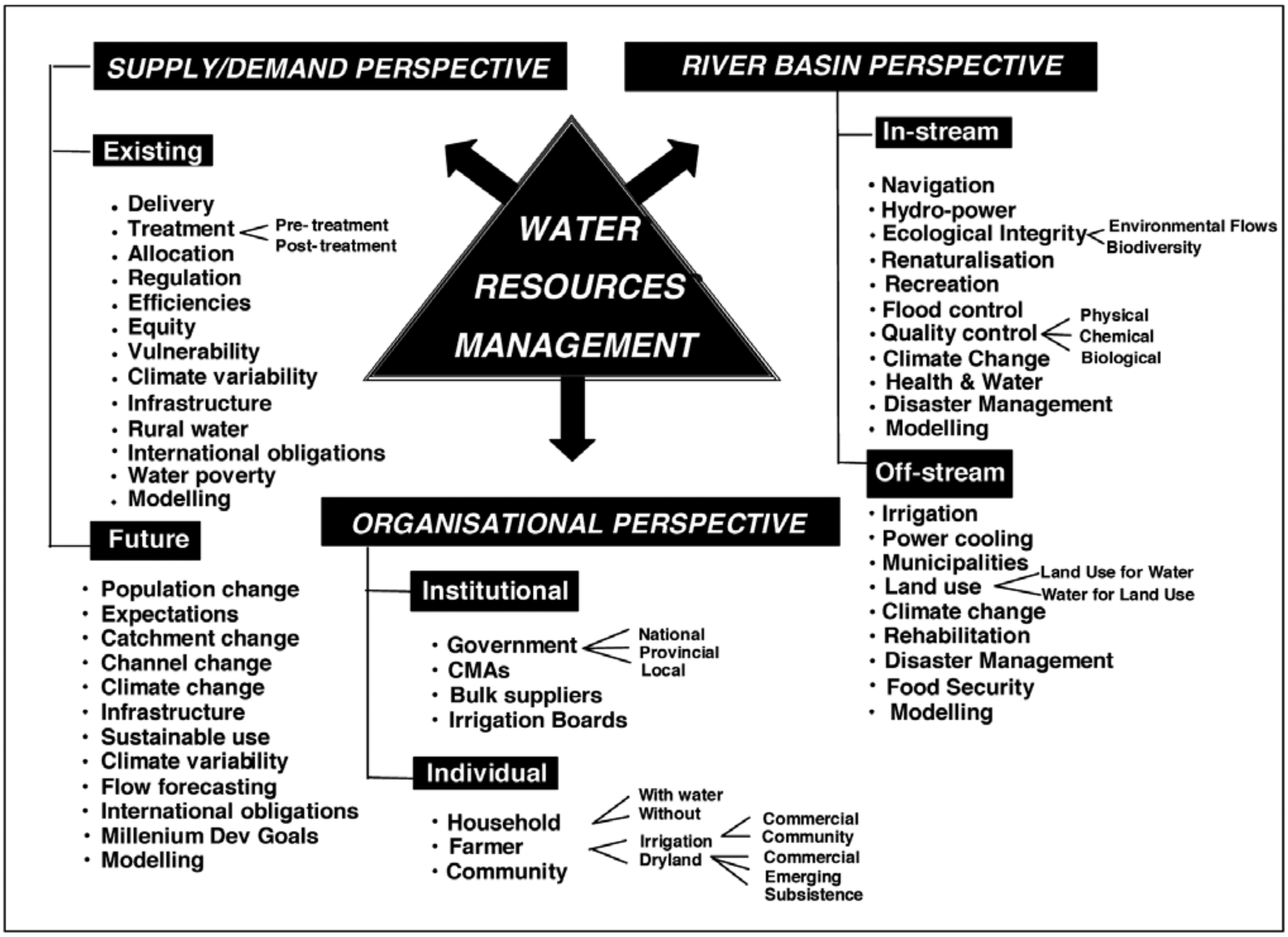


Figure 2.2: The interlinked nature of water resources management (Schulze, 2005a)

2.2 Major paradigm shifts have taken place in water resource management since the early 1990s

Adding to the many challenges which water managers face is the fact that the past decade or two has seen a number of paradigm shifts in water resources management which are likely to intensify in the future; in some measure also as a manifestation of climate change.

Some of the paradigm shifts, according to Schulze (2005b), place a greater emphasis than was the case in the past on

- environmental issues (vs. only functional engineering systems)
- sustaining the resource of water (vs. only harnessing it)
- conflict management in water (vs. problem solving)
- assessing the value of water (vs. to only the volume of water)
- forecasting hydrological responses (vs predicting extremes)
- addressing water quality issues (vs. only those on water quantity) and
- whole, and holistic, catchment management (vs. focusing only on channel and reservoir control).

2.3 Differences in characteristics influencing IWRM exist between more developed and lesser developed countries

To this day large tracts of Africa remain underdeveloped. Fundamental differences in infrastructure and capacity, as well as in economic and socio-political characteristics may be identified between more developed countries (DCs) and lesser developed ones (LDCs) which have a strong bearing on IWRM and the manner in which impacts of CC need to be contextualised in the water sector. These differences are summarized in Table 2.1.

More developed countries	Lesser developed countries
Infrastructure • High level of development; infrastructure generally improving • Infrastructure decreases vulnerability to natural disasters • High ethos of infrastructure maintenance • High quality data and information; well coordinated	**Infrastructure** • Often fragile; frequently in a state of retrogression • High vulnerability to natural disasters • Low ethos of infrastructure maintenance • Data and information bases not always available
Capacity • Abundant scientific and administration skills available • Expertise developed to local levels • Flexibility to adapt to technological advances	**Capacity** • Limited scientific and administration skills available • Expertise highly centralised • Often in survival mode; technological advances may pass-by
Economy • Mixed, service driven; buffered by diversity • Economically independent and sustainable • Long term planning perspective • Wealthy; money available for IWRM and climate change adaptation	**Economy** • High dependence on land; vulnerable to climate • High dependence on donor aid, NGOs • Shorter term planning perspective • Limited wealth; less scope for IWRM and climate change adaptation
Socio-Political • Low population growth • Generally well informed public; high appreciation for science • High political empowerment of stakeholders • Decentralised decision making	**Socio-Political** • High population growth; pressure on land • Generally poorly informed public; less appreciation for science • Stakeholders often not empowered; afraid to exert pressure • More centralised decision making
Environmental Awareness and Management • High level of expectation in planning and IWRM • Desire for aesthetic conservation	**Environmental Awareness and Management** • Lower level of expectation and attainment of goals • Need for basics for living

Table 2.1: Characteristics influencing IWRM, and hence responses to climate change, in more developed vs. lesser developed countries (after Schulze, 1999)

Because of the high levels of expectation of IWRM in developed countries, as well as a pro-active perspective and a generally non-life-threatening environment and infrastructure, IWRM in developed countries can focus more on long-term issues, on quality of life and on the environment, including (Schulze, 1999) preservation of the environment (with a focus on aquatic ecosystems), the re-naturalisation and rehabilitation of the catchment and its receiving streams, matters pertaining to non-point source pollution, demand management of water and potential impacts of climate change on water resources, with attendant adaptation strategies.

As a consequence of poorer infrastructure in LDCs, higher vulnerability to natural events and often being in survival mode, IWRM in LDCs frequently has to address more immediate issues (Schulze, 1999) such as:

- creating basic water supplies (vs. supplying water of the highest quality in the DCs)
- managing the water supply (vs. demand management)
- poverty alleviation (vs. quality of life enhancement)
- harnessing the environment (vs. sustaining it)
- short term needs (vs. long term perspectives)
- climate variability, both intra- and inter-seasonal (vs. climate change)
- creating an infrastructure (vs. maintaining, improving it).

With the tendency for issues on IWRM to emanate largely from DCs, it is necessary to focus on problems of IWRM, such as those above, which are likely to have strong bearing on adaptation strategies to CC in LDCs.

3. How does climate change link with the hydrological system?

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

$$Q = P - E +/- dS$$

where Q equals streamflow, P is precipitation, E represents evaporation, made up of transpiration (E_t), evaporation from the soil surface (E_s) and free water evaporation (E_w) from intercepted water and that from open water surfaces (lakes, dams, river channels), and dS constitutes the changes in storage of soil and groundwater. With CC the primary forcing function, viz. a change (d) in CO2, alters E_t in the hydrological equation directly through a reduction in transpiration, while the secondary forcing function, i.e. the resultant change in temperature (dT), enhances both E_s and E_w and simultaneously, through changes in atmospheric pressure belts, alters precipitation patterns and attributes and, consequently, dS (Schulze, 1997).

By itself, increased atmospheric CO2 concentrations (Fig. 2.3) can have significant hydrological repercussions through reductions in stomatal conductance of plants, thereby reducing maximum and thus actual transpiration rates, with the reductions varying between C3 and C4 plants, as well as the plants' biomass and the level of soil moisture content (Schulze, 1995; 2003).

Temperature changes, by themselves, will have direct and indirect bearing on water resources through changes (Schulze, 2003), for example, in

- potential evaporation from dams or as an increased atmospheric demand on the soil/vegetation complex, and hence
- soil moisture, and consequently vegetation/crop water use and the potential to generate runoff and, therefore, changes in
- total ("actual") evaporation from the soil/vegetation complex and hence partitioning of rainfall into evaporation and runoff components,
- irrigation practices, with different 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, severities, durations and spatial extents.

At different scales of space and time, any changes in the magnitude of rainfall, its intensity, duration, seasonality and persistence of wet/dry rainfall sequences will all affect the partitioning of rainfall into its different runoff generating components, and hence river flows and groundwater recharge.

These changes (Schulze, 2003) may be grouped into

- changes in global scale circulation patterns such as those which result in El Nino-Southern Oscillation events with their associated droughts and floods, and furthermore with possible (but not yet confirmed) increases in, and southward movement of, tropical cyclone activity around southern Africa;
- changes in magnitudes of annual rainfalls, and their seasonal distributions, 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 resultant sediment yields;
- changes in the number of raindays, which would affect runoff generation, irrigation water demand and recharge to groundwater;
- changes in extreme events, including the possibility of simultaneously more flood events and droughts over a period of time, which would alter reservoir sizing and possible changes in hydrological design (e.g. spillways) and disaster management preparation.

It should be stressed first, that these individual effects brought about by changes in greenhouse gas concentrations, temperature and rainfall will act in combination with one another, thereby either partially reinforcing or self-cancelling any hydrological impacts and, secondly, that the impacts of the individual drivers will not be spatially uniform within a region, with certain areas being more vulnerable than others to changes in hydrological responses (Schulze and Perks, 2000).

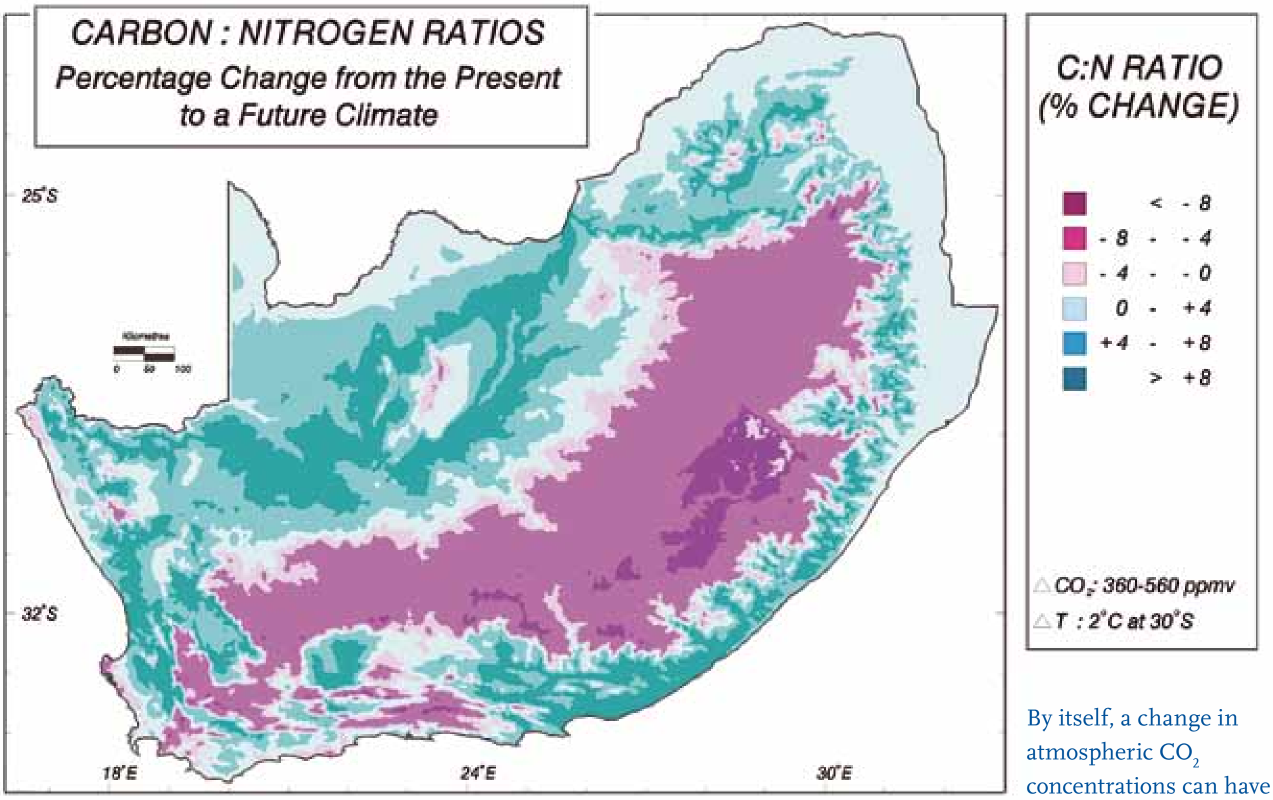


Figure 2.3: Carbon: Nitrogen Ratios

By itself, a change in atmospheric CO_2 concentrations can have important hydrological repercussions.

4. Why does the hydrological cycle amplify changes in climate?

Probably the most common statement made about climate change in relation to the water sector is that the hydrological cycle amplifies, or intensifies, in particular any changes in rainfall characteristics. Of the six causative factors of the amplification phenomenon identified in the literature (e.g. Bugmann, 1997; Schulze, 2000), two are highlighted in the context of climate change.

First, **Hydrological Responses Occur Non-Linearly**, with clear distinctions in responses needing to be made between processes occurring episodically (e.g. rainfall), vs. cyclically (e.g. evaporation), ephemerally (e.g. lateral flows) or more or less continually (e.g. flows from the groundwater store). Additionally, certain responses are rapid (e.g. surface runoff), while others occur 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, and this non-linearity is exacerbated when the natural system is replaced by anthropogenic systems which introduce land use changes or reservoirs, or when climate drivers change.

Secondly, **Runoff Responses Require Thresholds to Occur**, with surface runoff generation, for example, involving two distinct processes each with a different threshold in order to occur. On the one hand, overland flow on high ground occurs when rainfall intensity exceeds the infiltration rate into the soil, while saturated overland flow 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 saturated zone of varying extent over time, then being converted to overland flow. In both cases a threshold of rainfall needs to have occurred to trigger a response. Similarly, subsurface flow generation is determined by two distinct thresholds which need to be exceeded, with the threshold for interflow (i.e. subsurface lateral flow down a hillslope) to occur depending, inter alia, on soil horizonation, different hydraulic conductivities along a hillslope toposequence as well as on slope shape (e.g. concave, convex), while the threshold for baseflow to occur is determined, inter alia, by aquifer properties, the amount of recharge to groundwater that has taken place 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 subjected 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. In all the above examples, thresholds need to be exceeded for hydrological responses to be triggered, but once they have been exceeded, the responses often proceed at an accelerating rate with changes in rainfall.

5. Scale issues and challenges in integrating climate change studies with water resource management

Scale issues in climate change studies usually focus on problems associated with downscaling from Global Climate Models to more appropriate local scales applicable to hydrological modelling. This discussion will, however, highlight some more generic questions related to scale by

- first making some general observations on decision taking at the “scales that count”,
- thereafter, addressing some considerations of spatial scales when adapting to climate change within a context of IWRM,
- followed by a parallel discussion, but on temporal scales and, finally
- outlining the manner in which hydrologically homogeneous response zones, termed Quinary Catchments, have been delineated in South Africa for climate change impact studies.

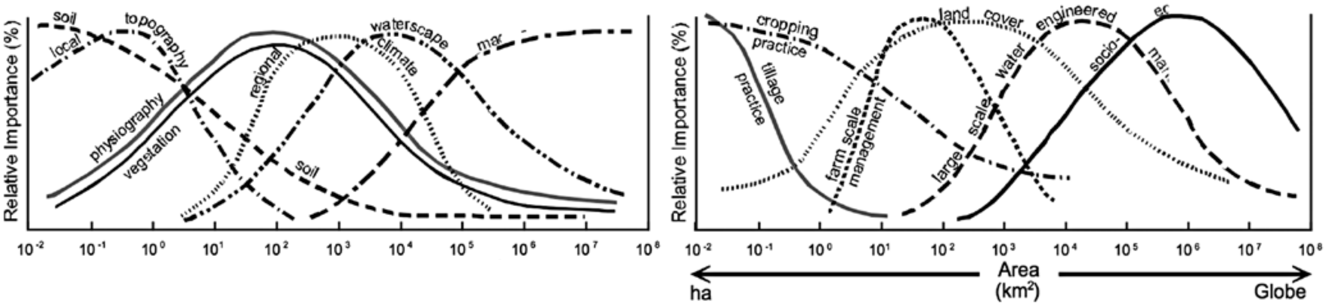


Figure 2.4: Natural heterogeneities (top) and anthropogenic influences (bottom) occur across a range of spatial scales, but dominate hydrological responses over a narrower spectrum (Meybeck et al., 2004)

5.1 Making decisions at the scales that count: some general observations

Hydrological processes and responses on a catchment are complex and take place across a range of spatial and temporal scales, as do those land use practices and socio-economic processes which impact on water resources. All of these will be affected by the magnitude, direction and rate of climate change.

However, within this complex hydrological landscape, different natural and anthropogenic influences dominate hydrological system responses depending on the scale involved.

This is illustrated in Figure 2.4 (top) for the natural hydrological system (Meybeck et al., 2004; Schulze, 2004) through the greater dominance of

- soil properties and local topography (slope, aspect, altitude), which are relatively invariant (i.e. non-changing over time), as major hydrological response agents at small catchment scale (~ < 101 km2), vs
- physiography (i.e. the macro-landscape) and, in phase with that, the more variant (i.e. changing over both space and time) broad vegetation units, as well as regional climate (e.g. precipitation, temperature and evaporation patterns), the waterscape (e.g. channels, floodplains, wetlands, lakes and estuaries with their associated ecosystems) and macro-climate (synoptic scale events), all of which are dominant influences on hydrological responses at the larger catchment scales of ~ 101 to 105 km2 and which are affected by CC.

Similarly, anthropogenic influences on the hydrological system are also scale dependent (Figure 2, bottom; Meybeck et al., 2004; Schulze, 2004) with, for example:

- tillage practices, cropping practices and farm scale management, all of which will be affected by CC, having major impacts at local hydrological scales, but hardly (or much less so) at larger catchment scales, whereas
- land use and cover as well as water engineering systems (e.g. reservoirs, irrigation, inter-basin transfers) and the status of socio-economic development (e.g. LDCs vs DCs), may all be impacted upon by CC and, by themselves or in combination, may change natural hydrological regimes (Meybeck et al., 2004).

The scale at which adaptation to CC within a framework of IWRM should take place is therefore not one that is easy to answer. As a general observation, however, the appropriate temporal and spatial scales of operation of adaptation within IWRM are those scales at which the policy makers, catchment managers and stakeholders believe that they can achieve their set(s) of objectives for future sustainable resource use. These scales will be defined, inter alia, by

- how effectively an area can be managed,
- what level of development had previously been attained in the area,
- the uniformity of the catchment in relation to biophysical resources (e.g. water, agriculture), human resources, wealth and ease of communication with stakeholders, all of which are influenced by constraints of politics, finances and levels of bureaucracy (Schulze, 1999; 2004).

Within an overarching 'scale of operation' any IWRM plan which includes CC adaptation options will, therefore, have to contain a hierarchy of intermediate and internal smaller space and shorter time scales, in order to define interim stages of implementation, goals or milestones (Schulze, 1999; 2004).

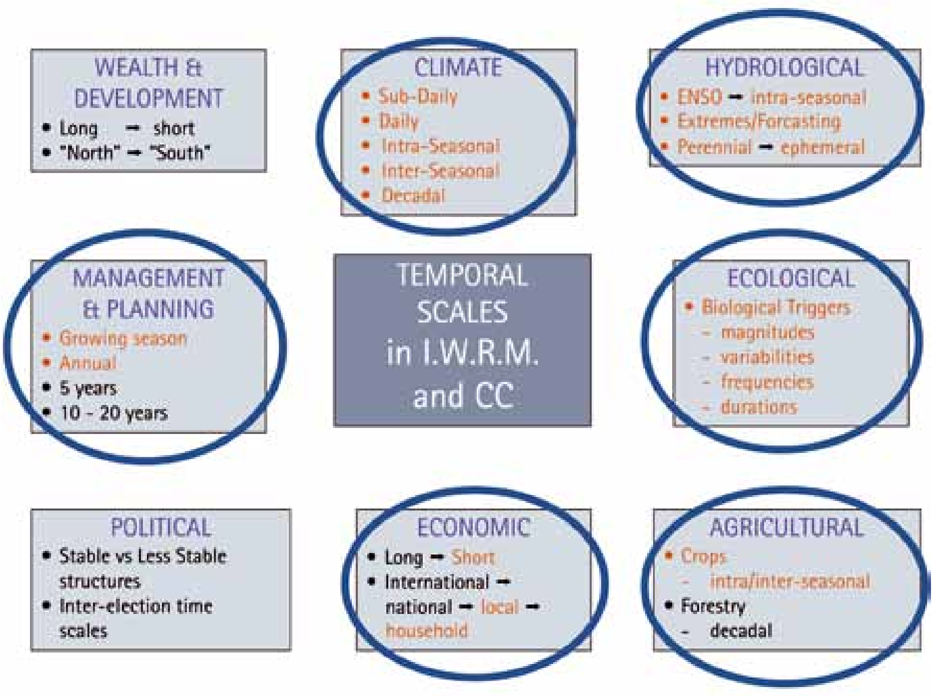


Figure 2.5: Temporal scales in Integrated water resources mangement (IWRM) and climate change (CC)

5.2 Considerations of spatial scales when adapting to climate change within a framework of IWRM

In considering CC, IWRM has to take consideration of all, or some, of the following spatial scales (fig. 2.5):

- global scale, e.g. issues related to water conventions or El Niño-Southern Oscillation (ENSO) scale events
- international scales, e.g. in regard to problems of inter- and/or transboundary rivers
- the national scale, e.g. national water management strategies or agendas
- catchment scales, with each catchment having its own unique water issues
- local government scales with their local, often administrative, initiatives or governance problems
- community scales, at which water availability and ease of access to water may be major issues and
- household scales which, especially in LDCs, may include problems of household water and food security.

Spatial scale issues in the water sector often reflect the overall level of economic development, e.g. in poorer countries or regions within a country, the space scale tends to be much smaller, determined by factors such as the distance range at which one can mobilise communities, or the availability of land around a village, or access to local water sources (Schulze, 1999).

In a rural African context, Frost's (2001) observations on IWRM also hold true for adaptation strategies for CC in that the larger the spatial scale, the more difficult management, and hence adaptation, becomes with respect to

- the range of local resources available and
- the number and diversity of stakeholders who have the necessary skills, interests, resource endowments, as well as capacities for management. This implies that agreement/consensus is not easy, and plans of action become more complex and time-consuming.

When putting adaptation strategies into practice "on the ground", Frost's other observations equally hold true in that when focussing at too broad a scale, it is often impossible to keep in perspective the 'fine-grained variation' embodied in all the various adaptation procedures and one runs the risk of overlooking local features, local needs, local circumstances and/or local aspirations, especially of the poor within the catchment, while on the other hand, when focussing on too fine a scale, there is a danger of losing sight of the wider context of adaptation strategies and thus losing sight of the overall governing processes of IWRM (Frost, 2001).

One often overlooked spatial scale consideration related to CC is that not only are shifts in climate and associated land uses going to take place geographically by latitude and longitude, but that migration of temperature and precipitation patterns in mountainous areas will also be altitudinal, and that there will potentialy be changes with in land use with altitude as well as in the form of precipitation (snow vs rain) and its intensity.

5.3 Considerations of temporal scales when adapting to climate change within a framework of IWRM

From the above discussion it becomes evident that, just as with spatial scales, time scales in IWRM should not be viewed as static when consideration is given to CC adaptation options. Rather, temporal scales should be perceived as a hierarchy of overlapping scales (Schulze, 1999) juxtaposed within one another.

These include

- climate scales, not only at the decadal time frame of the climate change phenomenon per se, but also at the scales at which they will manifest themselves in day-to-day life at inter-seasonal, intra-seasonal and daily time scales, because climate at these various scales 'drives'
- river flow scales, which for communities dependent on surface water will range from the irregular but recurring high flow and drought sequences related to the ENSO 'cycles' at multiple year scales, and the inter-seasonal variability of flows associated with such; or the seasonality and concentration of streamflows within a year at a given location; to intra-annual flow variability; or the forecastability of river flows with lead times from days up to a season ahead; or to the recurrence intervals of floods or droughts of a specific magnitude; while for communities dependent on groundwater the temporal recharge patterns and water table fluctuation are of importance;
- aquatic ecosystems time scales, which are dependent on magnitudes, frequencies and durations of low flows and high flows as biological triggers, or by the number of biologically significant positive hydrograph reversals in a river, all of which are projected to alter with CC;
- agricultural time scales, in which the CC:IWRM interrelationship the dynamics of the interdependence of crops on water (in the soil and from the river) and water (in rivers and the soil) on crops becomes an important (albeit complex) one;
- economic time scales, ranging from longer term internationally significant phases of growth vs. recession, to the way these play out at national level, to regional or local to shorter term time scales that affect the individual rural subsistence household;
- political time scales, in which a distinction needs to be made between essentially stable government structures, in which CC adaptation strategies are more easily effected than under potentially unstable government structures; and also inter-election time scales for national and local government structures, during which promises of water reform and adaptation plans may be made;
- management and planning time scales, often of the order of 10-20 years and into which planned adaptation has to slot; and
- wealth/development level time scales, where wealthy countries tend to have longer term planning horizons which can accommodate CC adaptation strategies more readily than poorer countries, which tend to have shorter planning horizons (Schulze, 1999; 2004).

In summary, it needs re-emphasising that the time scales at which CC adaptation strategies within a framework of IWRM are best initiated and effected are related to the scales at which people on the ground are both being impacted upon by the availability of land and water resources, and are impacting upon these resources.

5.4 Delineating hydrologically homogeneous response zones for climate change impact studies: the concept of the quinary catchment

An appropriate spatial scale which is relevant to practical, day-to-day adaptation decisions in regard to CC is one from which hydrological and associated agricultural responses are considered homogeneous. But, what is an appropriate spatial scale? In southern Africa, for example, the contiguous area of ~1.267 million km2 comprising South Africa, Lesotho and Swaziland has been delineated in 22 Primary Catchments (fig 2.6), each of which has been sub-delineated into smaller Secondary, even smaller Tertiary and finally into 1,946 fourth level Quaternary Catchments (QCs). Until very recently these QCs had been regarded as homogeneous enough for operation analyses and day-to-day decision making. However, over half of these QCs have been defined as still being too heterogeneous hydrologically for effective water management (Schulze and Horan, 2008), particularly in their responses to perturbations in climate.

Therefore, a 5th level of Quinary Catchment has now been delineated by sub-dividing the 4th level QCs into hydrologically and agriculturally more homogeneous spatial units with respect to rainfall, evaporation, soils and slopes (Schulze and Horan, 2008). Each QC was sub-delineated into 3 Quinaries of unequal size using Jenks' optimisation procedures based on natural breaks in altitude. Altitude was used as the criterion for sub-delineation as it is a strong determinant of rainfall, temperature (and thus evapotranspiration) and slope gradients which together exert strong influences on soil properties and land use, and hence on stormflow and baseflow generation, peak discharge and sediment yield. Consequently RSA, Lesotho and Swaziland are now divided into 5,838 Quinary Catchments (Schulze and Horan, 2008). For water resources and CC impact studies, each of the Quinaries has been populated with 50 years (1950-1999) of historical daily climate data, as well as with daily climate data downscaled from numerous GCMs from the 2007 IPCC Fourth Assessment Report for present, intermediate future (2046-65) and more distant future (2081-2100) climate projections, and with hydrological soils attributes, land cover attributes and slope gradients.

It is only at such a local scale, at which homogeneous responses to climate change are likely to occur, that it is believed that meaningful adaptation strategies can be developed and implemented. Projected hydrological responses, however, will need to be simulated and in thefollowing section hydrological model requirements for effective climate change impacts studies are discussed and evaluated.

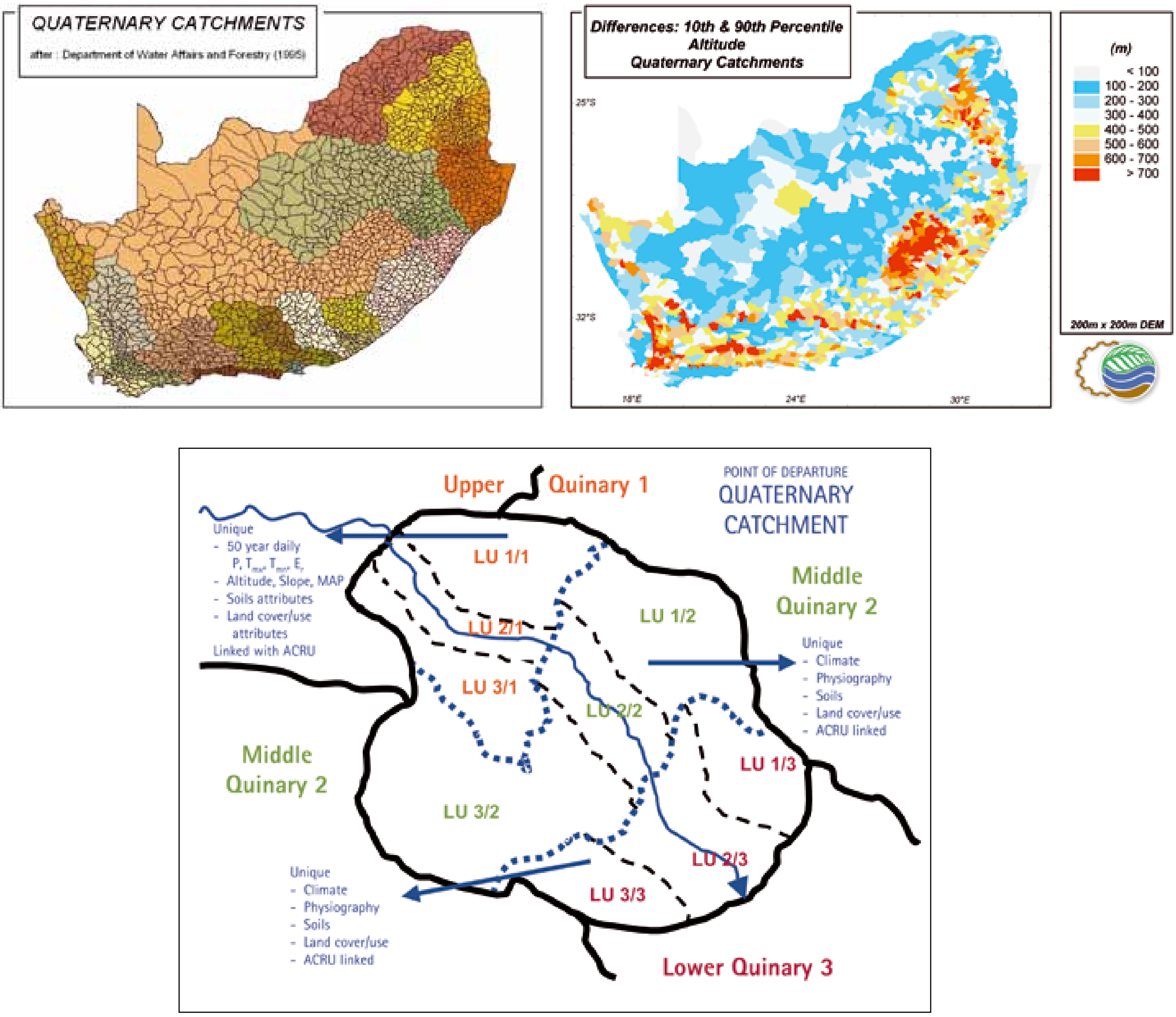


Figure 2.6: Point of Departure Quaternary Catchments

6. On issues of modelling impacts of climate change on the hydrological system

6.1 The Significance of the Water Sector in Climate Change Studies

The superpositioning of a potential "speeding up" of the hydrological cycle through climate change in an era in which water management is already in a state of flux does not simplify matters for the water practitioner; particularly if one bears in mind the amplification effects of changes in rainfall attributes on runoff responses and the vital links that water has to other major natural cycles (e.g. the nitrogen and carbon cycles) and sectors (e.g. agriculture, transport, health or risk management). Appropriate hydrological models will become an increasingly important tool in addressing the consequences of many of these paradigm shifts. A logical question raised is "What is required of a suitable simulation model for effectively assessing impacts of climate change on the hydrological system?" (Schulze, 2005b)

6.2 Model Requirements for Effective Climate Change Impact Studies

a. What Constitutes the Hydrological System Under Investigation?

Modelling impacts of climate change in hydrology involves three "streams" of action which need to be merged (Schulze, 2005b). These are illustrated in Figure 2.7. Climate change demands an innovative approach to modelling hydrological processes, because perturbations in the drivers of these processes (e.g. dP, dT and dCO2 and its feedbacks on transpiration) will result in changes in evaporative demand, in partitioning of rainfall into the different runoff components (i.e. stormflow, baseflow) and, hence, in water quality. In essence these response changes occur on the landscape component of the catchment; on which natural land cover and soils properties may already have been altered by human actions. Key climate

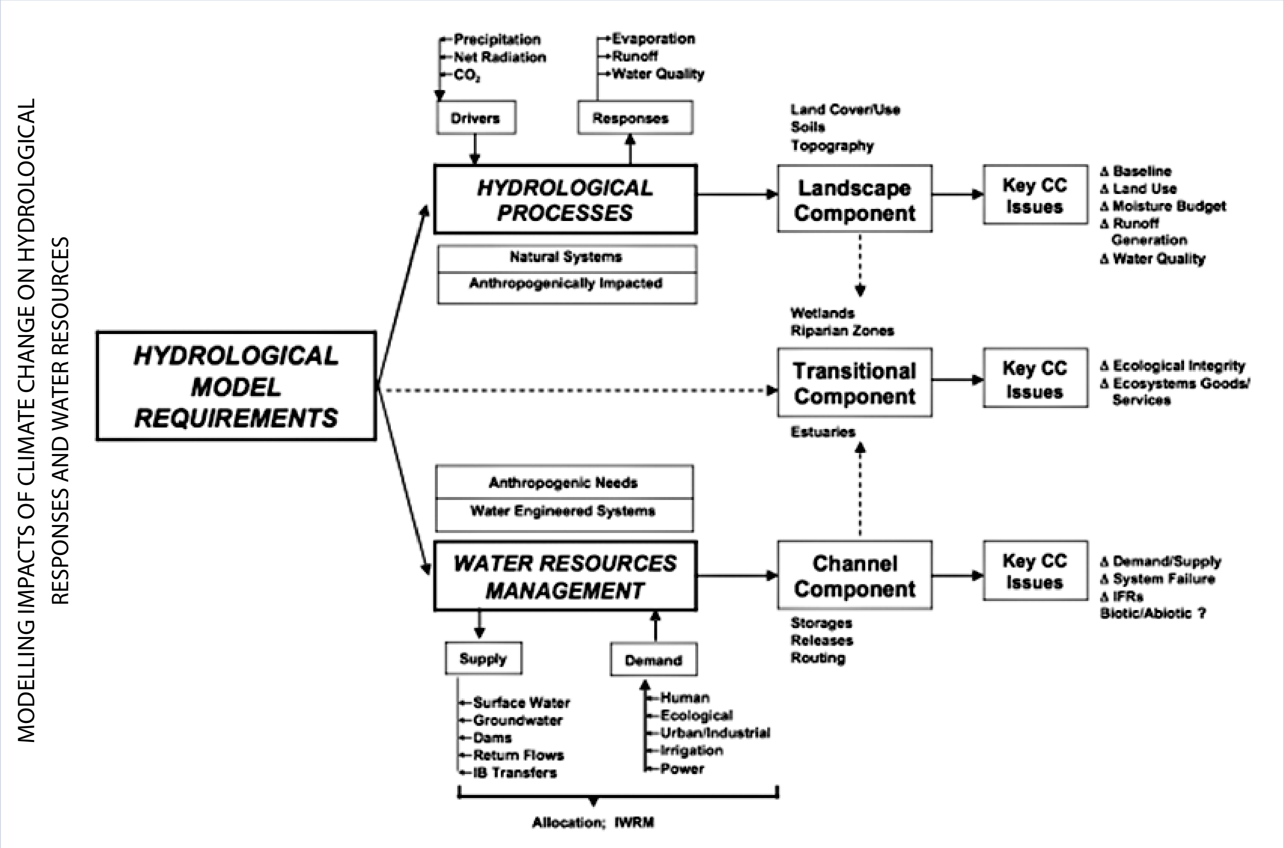


Figure 2.7: Hydrological model requirements under conditions of climate change (Schulze, 2005b)

change issues in regard to the landscape component include alterations to the hydrological baseline against which any further impacts are to be assessed, as well as spatial changes in land use patterns and, hence, in runoff/water quality responses (Schulze, 2005b).

Aditionally, water resources practitioners and managers have to grapple with balancing supply of water (be it from rivers, groundwater, impoundments, return flows or water transfers) with demand for water (e.g. from basic human and ecological needs to requirements for the urban/industry sectors, power generation and irrigation), and to allocate available water in a sustainable manner through holistic planning, i.e. IWRM. In most instances this involves manipulations of the channel component of the catchment through "controls" of storage, releases and routing of water. Key climate change related challenges generally revolve around engineering issues such as changes in the supply of and demand for water; changes to design criteria of hydraulic structures (e.g. dam spillways, stormwater drains) in regard to potential system failure; environmental consequences of changes in natural flow regimes through dam construction or inter-basin transfers, including changes to flow requirements for aquatic habitats and other abiotic/biotic effects downstream (Schulze, 2005b).

Wedged, in a manner of speaking, between the landscape and the channel are the transitional components of the hydrological system, such as wetlands, riparian zones and estuaries. These components are frequently in delicate equilibria, which may "flip" as a consequence of landscape and channel manipulations. Under conditions of global warming these elements may become even more fragile and/or sensitive, and key challenges will be to assess changes in ecosystem goods and services (Schulze, 2005b).

For pro-active water resource management into a future with changed climates, all the above challenges have to be met explicitly or implicitly by appropriate modelling. Hydrological models therefore have to meet certain requirements in regard to process representations and model structure and some of these are identified and discussed below.

b. What Requirements Does this Place on Process Representations and Structure in Hydrological Models?

i. The Need to be Able to Model Explicitly the Dynamics of Different Streamflow Generation Mechanisms

"Streamflow is not simply streamflow"; its different components are generated by different mechanisms, have different hydrological functions and are generated from different (and dynamic) source areas within a catchment, and all of these factors likely to alter with climate change. For example (Schulze, 2005b),

- overland flows, which may be generated either from connected (adjunct) impervious areas, from saturated zones of variable areas or when rainfall intensities exceed infiltrability; have short residence times of minutes to hours; are event-based; remove/transport sediments and other surface material (e.g. fertilizers, pesticides, industrial pollutants) and are critical in peak discharge estimation as well as in water quality determination
- subsurface stormflows have slower response times and different water chemistries
- baseflows, which are sustained by recharge from preferential zones within a catchment, have long memories, display slow decay, exhibit a different chemistry again and have a different criticality in maintaining different biological functions.

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

ii. The Need to Distinguish Clearly Between Landscape Based and Channel Based Processes

Within morphologically similar landscapes, hydrological processes down hillslopes tend to be spatially repetitive; with the hillslope elements of the catchment being the generators of streamflow in its different forms. Under conditions of climate change the landscape processes, which may have been modified by land use and land management, need to be modelled separately from channel processes by water budgeting procedures which have to account, inter alia, for both the feed-forwards and feedbacks associated with the drivers and buffers of climate change, and which are not always fully understood and/or accounted for by the process representations in hydrological models (Schulze, 2005b).

Channel processes, on the other hand, tend to be additive with catchment size, are attenuated by channel characteristics of slope, shape and roughness as well as by transmission losses to floodplains, banks and alluvial beds and by open water evaporation, are manipulated by engineering works (e.g. by abstractions, diversions and impoundments, Figure 2.7) and need to be modelled hydraulically (as distinct from hydrologically) with often complex equations describing relatively well understood relationships.

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

iii. The Ability to Model Hillslope Processes

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

iv. The Ability to Model the Different Processes which may Dominate in Different Climatic Regimes

Globally the wide climatic range with annual precipitations ranging from < 50 mm to > 5 000 mm; with some falling as low intensity rain, some as snow, and some associated with high intensity convective storms, coupled with high intra- and inter-seasonal variability of the precipitation; and with the precipitation falling onto terrain ranging from steep montane to undulating hills to plains, all implies a highly variable spatio-temporal conversion of precipitation to streamflow, as well as a regionally and seasonally variable partitioning into overland flows, subsurface stormflows, baseflows or snowmelt, where the groundwater table may or may not be "connected" to the channel, depending again on season and location.

The above all point to the hydroclimatic environment being a complex one. Further examples of this complexity include: Groundwater recharge, for example, may be through the soil matrix in more humid areas or by channel transmission losses in more arid zones. Evaporation losses, on the other hand, may be dominated by riparian zone processes, or by transpiration, or by soil water evaporation, depending on climatic and vegetation regimes, or be influenced strongly by slope and aspect. Further, mountain catchment hydrology can be dominated by poorly understood precipitation; altitude gradients in terms of rain vs snow, rainfall intensities, numbers of rainfall days and event magnitudes, all of which change with elevation.

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

v. The Ability to Model Different Intensities of Land Management Practices

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

In an era when streamflow reduction activities, best management practices, payments for ecosystems goods and services and the „polluter pays“ principle are integral components of IWRM, and where in future land uses are likely to shift spatially and adaptive management practices applied, models have to be able to simulate differences in land use management (as against only land use) practices realistically under present and, importantly, future climatic conditions.

vi. The Need for a Daily Time Step, Conceptual-Physical, Process-Based and Non-Linear Dynamic Response Model

In order to simulate potential impacts of global change on hydrological processes and responses (the top component in Figure 2.7), in line with the model requirements discussed above, such a model would need to fulfil the following criteria (Schulze, 2005b):

- be conceptual, in that it conceives of a one or multi-dimensional system in which important processes and couplings are idealised
- be physical, to the degree that the physical processes are represented explicitly through observable variables (Eagleson, 1983)
- the model should, at minimum, be functional (i.e. threshold based, with initial and boundary conditions) in its process representation (Schulze, 1998)
- hydrological processes should account for present and future climate exchanges of water vapour, CO2 and energy (e.g. precipitation attributes, streamflow generation responses, evaporation and transpiration together with its CO2 driven feedbacks for modelling plant-soil interactions of future climates),
- which are then modified by characteristics of the

  - soil (surface infiltrability, subsurface transmissivity of soil water and water holding capacity);
  - land cover and land use/management (e.g. with above-ground attributes related to intra-seasonal biomass; surface attributes of soil protection by litter/mulch or of tillage practices; below-ground attributes relating to root distribution); and
  - topographic features of the landscape (e.g. accounting for differences in altitude, slope, aspect, toposequence and topographic position).
- 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), to cyclicity (e.g. seasons, evaporation), to hillslope processes (both on surface and below surface), to immediate responses (e.g. surface runoff from connected impervious areas; saturated overland flow), rapid responses (e.g. stormflow), ephemerality (e.g. discontinuous flows), more continuous responses (e.g. groundwater movement) and/or delayed responses (e.g. baseflow);
  - thresholds required for surface and subsurface streamflow processes to commence; and
  - dominant processes changing with scale or human interference (fig 2.2), including emerging properties (e.g. advection) and representations of disturbance regimes (e.g. drainage of fields, changes in streamflow regimes resulting from dam construction/abstractions/return flows), of gradual changes in land use intensification over time (e.g. agriculture and urbanisation), or of extensification (e.g. cropping in climatically marginal areas, or overgrazing impacts), or abrupt changes (e.g. those resulting from fires or flooding).
- As such the model should essentially be devoid of the need for calibration or parameter optimisation, since such parameters may be meaningless when extrapolating into future climates or future land uses.
- Furthermore, for most operational modelling, simulations should take place at daily time steps since the day is the shortest universal natural time step. Furthermore, climate variables from GCMs are now output at daily values, diurnality encapsulates (albeit not perfectly) many hydrologically related processes which are important in climate change studies (e.g. evaporation, transpiration and many discrete rainfall events), many operational decisions are currently, and in future climates will also be, made according to daily conditions (e.g. irrigation, reservoir operations) and daily climate data for present/historical climate conditions are readily available from a wide network of stations.
- Model output for impact studies of projected climate change within a framework of IWRM will have to address potential management conflicts across a range of spatial scales from upslope vs downslope conflicts, upstream vs downstream conflicts to those within vs. between Water Management Areas (Schulze, 2005b).

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

6.3 A Suggested Hydrological Model for Simulating Potential Impacts of Climate Change: The ACRU System

The ACRU agrohydrological modelling system (Schulze, 1995; Schulze and Smithers, 2004 and updates), which has been, and is currently being, used extensively in IWRM and climate change studies in southern Africa, complies with many of the premises and principles outlined above and is centred around the following objectives (Figures 2.8 and 2.11):

- It is a daily time step, conceptual-physical model,
- with variables (rather than optimised parameters values) estimated from physically based characteristics of the catchment,
- and the model revolves around daily multi-layer soil water budgeting.
- As such, the model has been developed into a versatile total evaporation model (Figure 2.11), structured to be highly sensitive to perturbations in climate drivers and to land cover, land use and management changes on the soil water and runoff regimes. Additionally, its soil water budget is responsive to supplementary watering by irrigation, to changes in tillage practices, enhanced atmospheric CO2 concentrations or to the onset and degree of plant stress.
- ACRU is a multi-purpose model which integrates the various water budgeting and runoff production components of the terrestrial hydrological system (Figures 2.12 and 2.13). It can be applied as a versatile model for design hydrology (including flow routing through channels and dams), crop yield modelling, reservoir yield simulation, ecological requirements, wet-

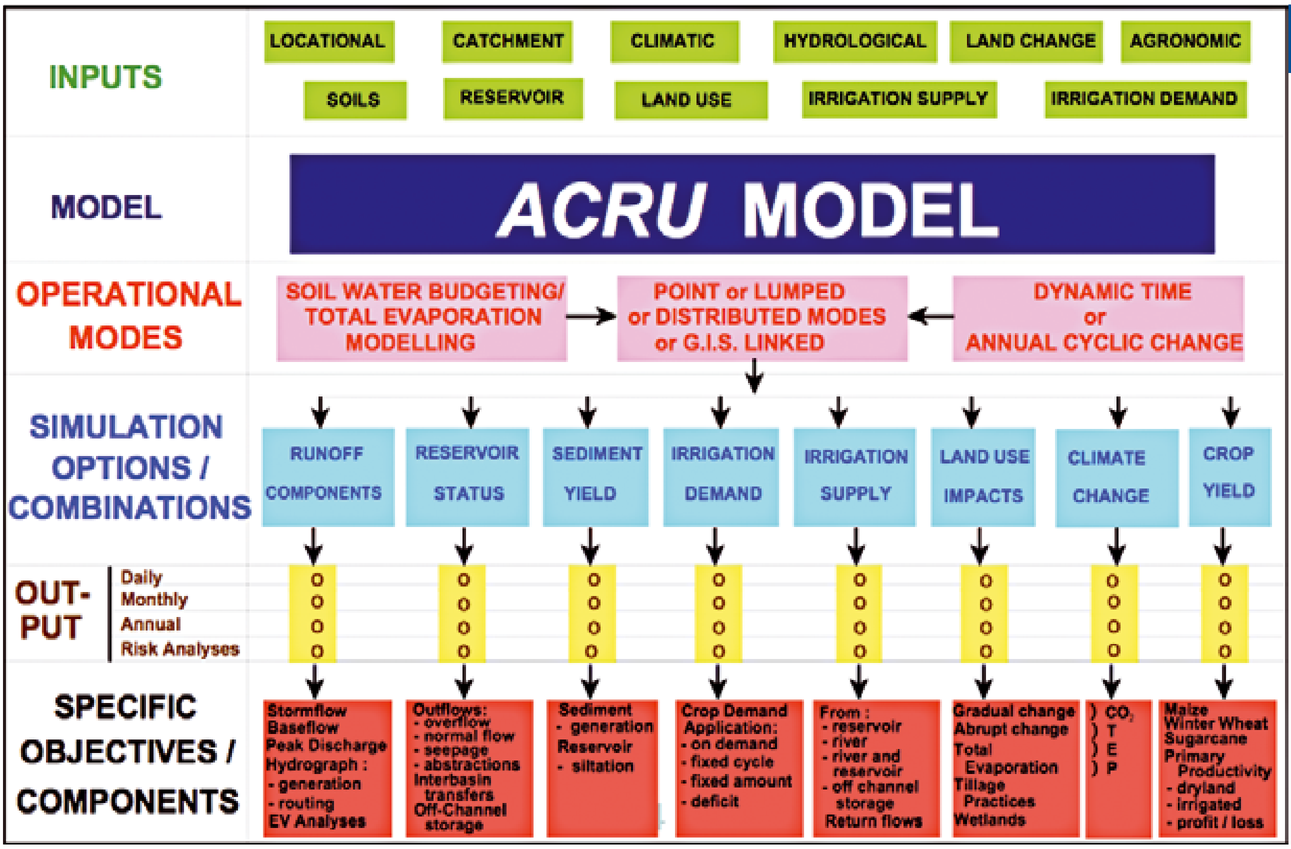


Figure 2.8: The ACRU agrohydrological modelling system: Concepts (after Schulze, 1995)

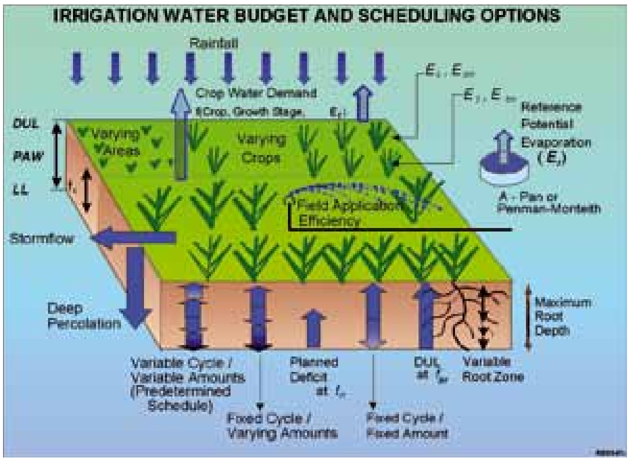


Figure 2.9: Schematic of Irrigation Water Demand and Scheduling Options Available in ACRU (after Schulze, 1995 and updates)

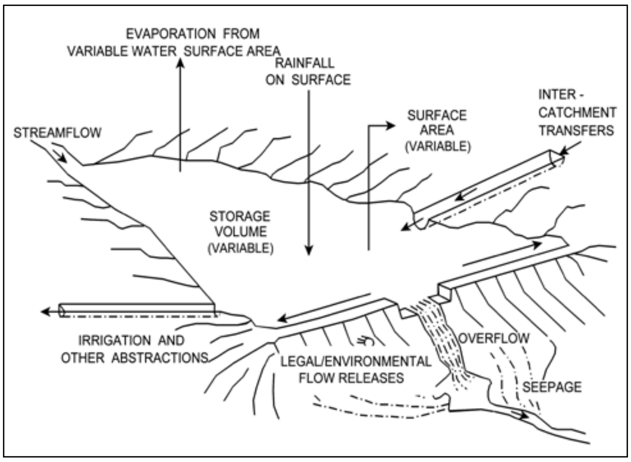


Figure 2.10: Schematic of the Reservoir Water Budget in ACRU (after Schulze, 1995)

lands hydrology, riparian zone processes, irrigation water demand and supply (fig 2.9), water resources assessment(fig 2.10), 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 (Schulze and Smithers, 2004).

- ACRU can operate at multiple scales, either as a point model or as a lumped small catchments model; on large catchments or at national scale as a distributed cell-type model with flows taking place from “exterior” through “interior” cells according to a predetermined configuration, with the facility to generate individually requested outputs at each subcatchment’s exit.
- The model includes a dynamic input option to facilitate modelling of hydrological responses to climate or land use or management changes over time, be these long term/ gradual changes (e.g. urbanisation or climate trends), or abrupt changes (e.g. construction of a dam), or changes of an intra-annual nature (e.g. crops with non-annual cycles).

- The ACRU model has been linked to the Southern African National Quaternary and Quinary Catchments Databases for applications across a range of scales in the RSA, Lesotho and Swaziland.

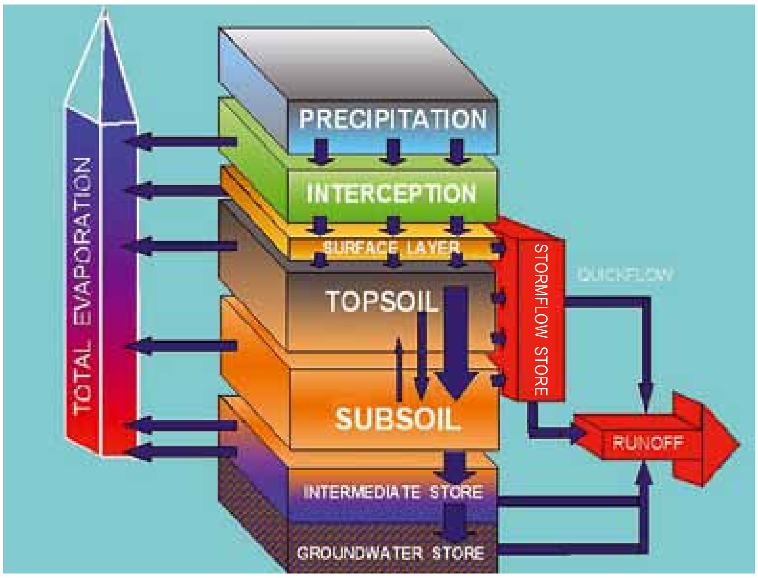


Figure 2.11: The ACRU agrohydrological modelling system: General structure (after Schulze, 1995)

The requirements for the "ideal" model with which to assess potential impacts of climate change in the real world of complex and holistic water management, have been shown to be both manifold and stringent. The ACRU modelling system meets many, but not all, of the criteria/requirements discussed in the previous section. Its conceptual-physical structure, operating on a daily time step and its multi-purposeness are without doubt attributes weighing in favour of its selection as a suitable model, as is its potential as a tool in resolving water management conflicts (e.g. land use impacts, water allocation, impacts on/of wetlands and reservoirs) at scales from small catchment to national, as testified by over 100 references (see Schulze and Smithers, 2004).

The model still requires improved process representations of interflow and baseflow releases, channel transmission losses and the addition of more water quality components. Despite these limitations, ACRU is, nevertheless, considered to be a modelling system highly suitable for evaluating impacts of climate change on the hydrology and water resources of southern Africa and elsewhere.

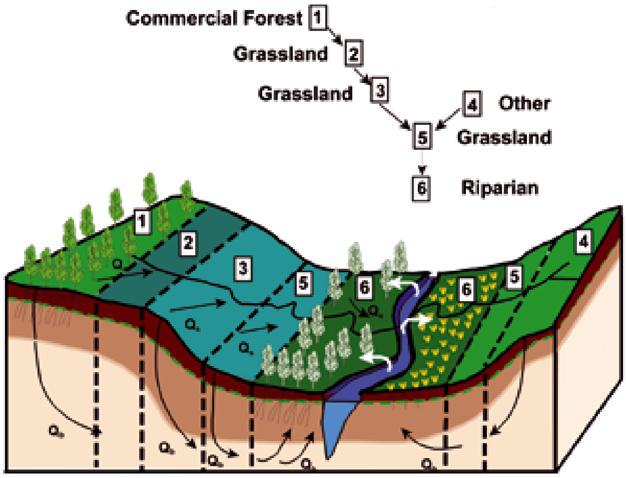


Figure 2.12: Hillslope and Riparian Zone Processes in ACRU (after Meier et al., 1997; Schulze, 2000b)

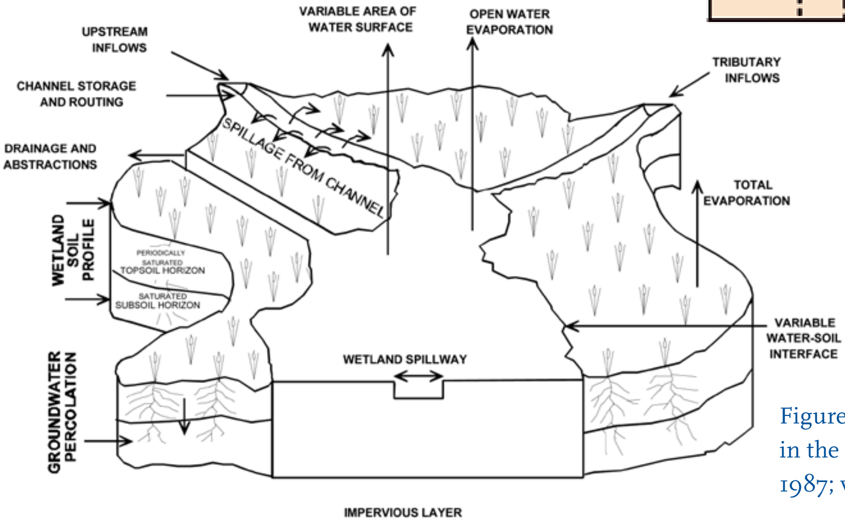


Figure 2.13: Concepts, Processes and Assumptions in the ACRU Wetlands Module (after Schulze et al., 1987; with modifications by Schulze, 2001d)

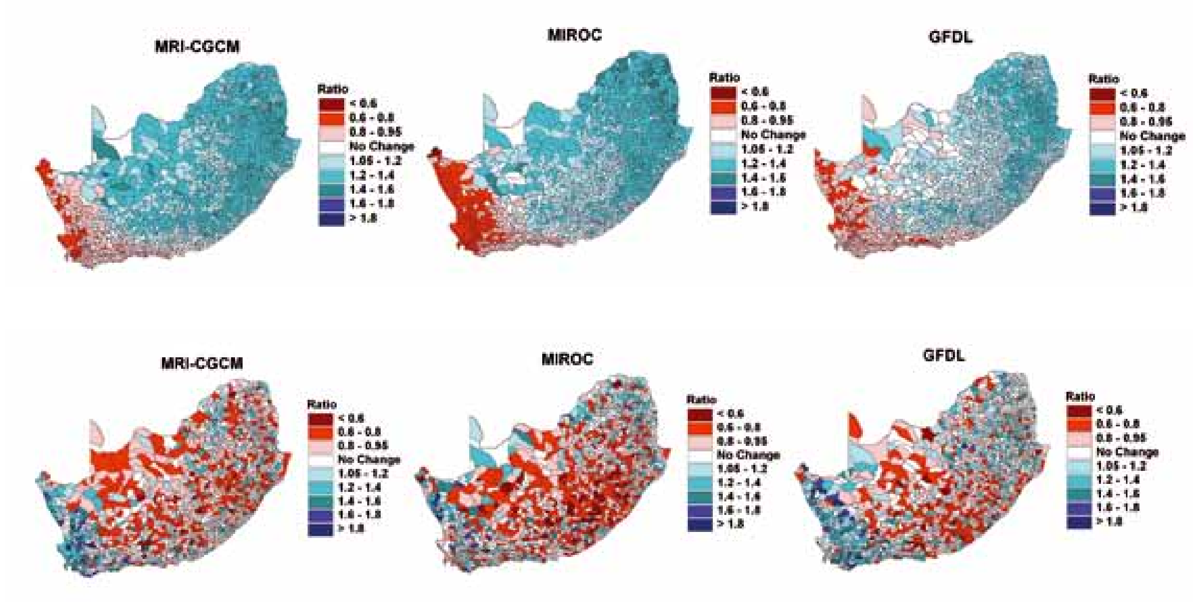


Figure 2.14: Ratio changes of mean annual precipitation (top) and the CV of annual precipitation (bottom) between intermediate future AR4 climates and the present

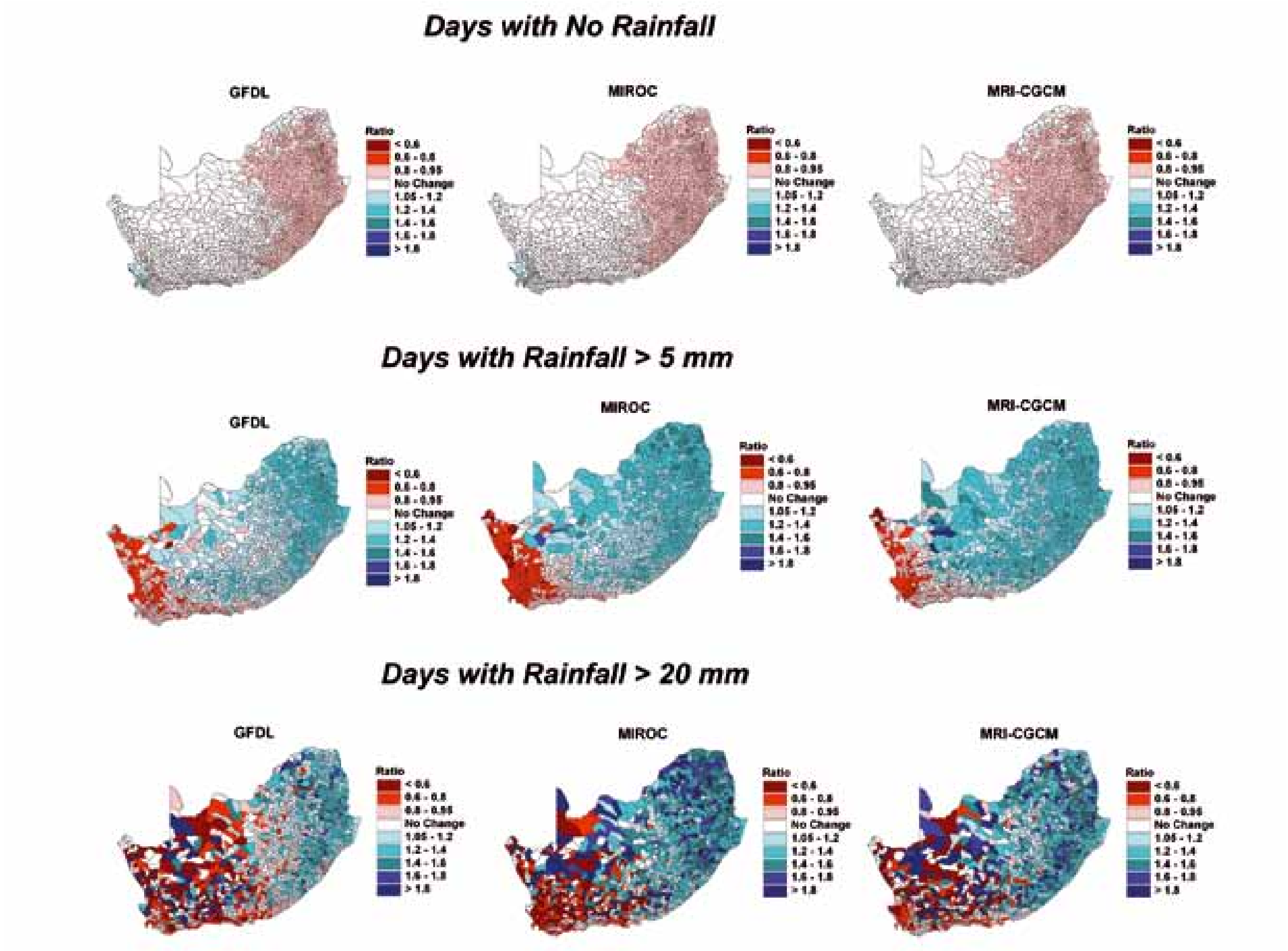


Figure 2.15: Ratio changes of days without/with rainfall between intermediate future AR4 climates and the present

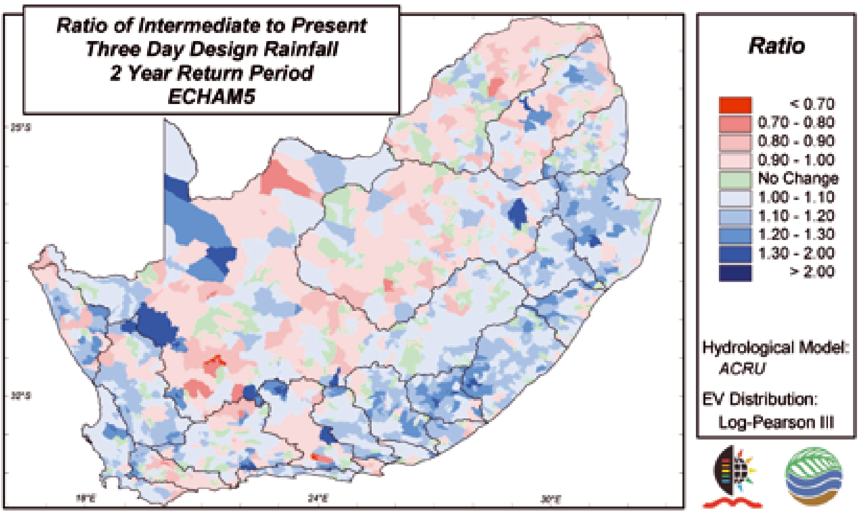


Figure 2.16

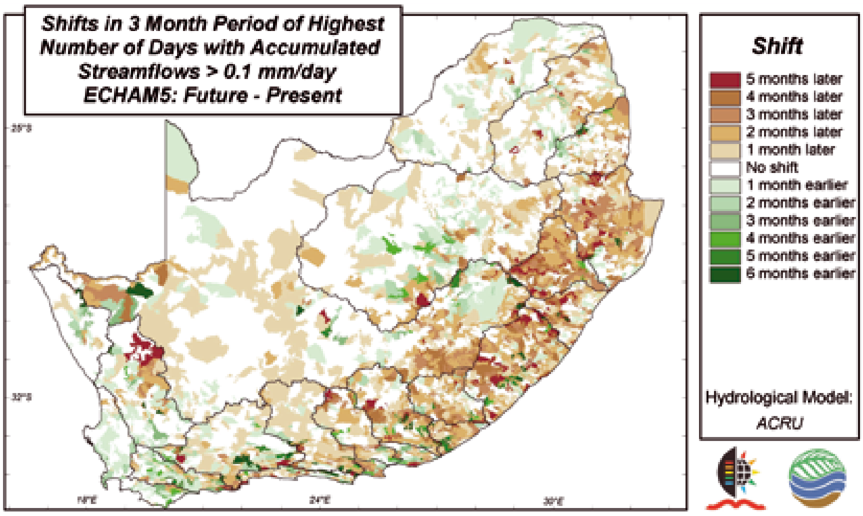
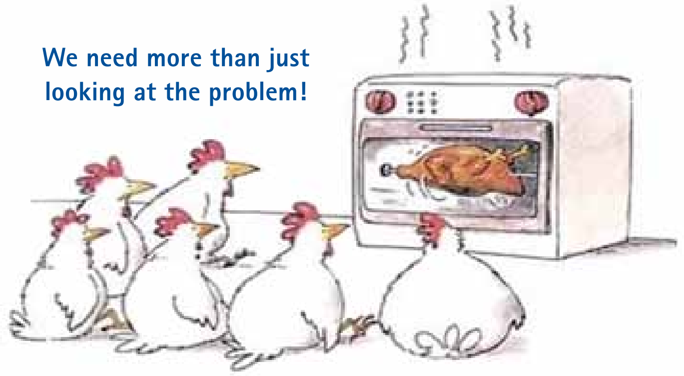


Figure 2.17

7. Adaptation issues

Having outlined some concepts of IWRM and its links to climate change, then raised issues of scales and model requirements for assessing potential impacts of perturbations of future climates on hydrological responses, the last major section now addresses the question of adaptation to climate change in the water sector. The focus is on experiences from South Africa, in the first instance outlining the existing legislation within which to strategise on adaptation, then focusing on the challenges of uncertainties, followed by some observations on adaptation by local water experts, the presentation of a conceptual framework on adaptation for South Africa and, finally, outlining some limitations to adaptation.



7.1 The Legislative Framework Within Which to Address Climate Change – The South African Case

A distinction has to be made between overarching national level legislation pertaining directly or indirectly to adaptation to climate change, and more water sector specific legislation.

a. The Overarching National Level Buy-in to Adaptation

i. The Constitution of South Africa of 1996

The South African state's commitment to adaptation is already imbedded in its Constitution in which it is stated that everyone has the right to access to "sufficient food and water" (Ch 2 Bill of Rights, Section 27b) and that everyone be provided with the right to an "environment that is not harmful to their ...well-being" and to have "the environment protected, for the benefit of present and future generations, through reasonable legislative and other measures" (RSA, 1996).

ii. The National Climate Change Response Strategy of 2004

More explicit than the Constitution regarding adaptation issues is the National Climate Change Response Strategy (NCCRS) which was published in 2004 by the Department for environmental affairs and Tourism. The NCCRS has the mandate of providing a roadmap for national climate policy based on the obligations to the Kyoto Protocol as well as publishing a National Adaptation Plan which focuses on vulnerable and/or threatened ecosystems and their associated goods and services (including those related to water) that support many livelihoods and maintain South Africa's environmental health and integrity (DEAT, 2004).

iii. The Climate Change Research and Development Strategy of 2008

Additionally, a Climate Change Research and Development Strategy with a 10 year vision is currently (2008) being completed by the Department of Science and Technology. This strategy aims at fostering/enhancing South Africa's knowledge on CC impacts, overall awareness and capacity as well as resilience in response to CC.

b. The More Specific Water Sector Buy-in to Adaptation

In addition to overall policy related buy-in in South Africa, the foundations for more water sector specific IWRM-CC links have been laid by the following:

i. The National Water Act of 1998

IWRM is firmly entrenched in the South African National Water Act (1998), which clearly declares "the need for the integrated management of all aspects of water resources and, where appropriate, the delegation of management functions to a regional or catchment level so as to enable everyone to participate" (NWA, 1998). Consequently, IWRM is the guiding principle of societal, environmental and economic needs and constraints, now and under conditions of climate change, which

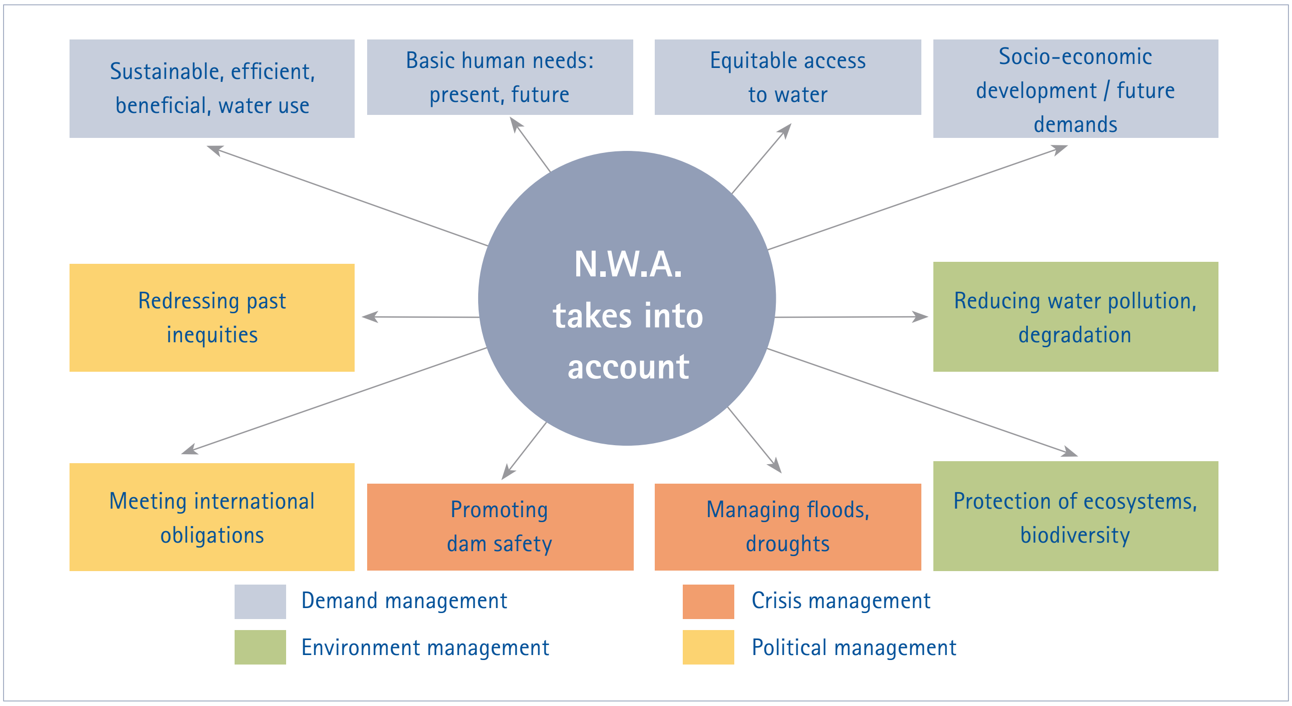


Figure 2.18: The South African National Water Act interfaces

is recognised explicitly in the Act (fig 2.18). Further, a strong emphases on, for example, top-slicing water for the human and ecological reserve as well as for downstream international obligations; assessments of streamflow reduction activities, also on water licensing/allocation; participatory processes that lead to equitable and sustainable development; and on flood/drought related disaster and risk management, provide a range of new challenges to the scientific and policy fraternities in regard to adaptation strategies to CC in the water sector.

ii. The National Water Resource Strategy of 2004

The objective of the 2004 National Water Resource Strategy (NWRS) is to take the National Water Act from legislation to a more practical implementation phase via obligatory IWRM which is to be effected through institutions such as Catchment Management Agencies and Water User Associations. Climate change features in the NWRS in the recognition that "the future will not be a simple extension of the past", with the interdependence of land use and climate change seen as the "two key influencing factors with respect to resource availability" (NWRS, 2004). Climate change is viewed in the NWRS as a cause of changing patterns of the water cycle by magnitudes and in variability as yet unknown. It is anticipated that the 2009 update of the NWRS will be more specific on issues of climate change in the water sector.

7.2 Adaptation in Practice

a. Challenges to Adaptation in the Water Sector

i. Many uncertainties remain in regard to potential impacts of climate change on water resources

Many uncertainties still remain regarding the question of potential impacts of climate change. These start with uncertainties surrounding emission scenarios of greenhouse gases, onto uncertainties revolving around the sensitivity of the global climate to enhanced emissions. The uncertainties then "explode" at each successive "downward" level, e.g. from global to the regional scale changes, climate variability, then to the possible biophysical impacts and eventually to resultant socio-economic impacts.

Uncertainties from climate science include questions on

- what is "background noise" (i.e. natural variability) vs what is already deemed a clear "signal" (i.e. trend) in an already variable climate?, or
- despite major advances (IPCC, 2007a) different GCMs still only predict general directions (e.g. increase in temperature), and sometimes they even still give mixed signals, and certainly varying magnitudes of change (e.g. on rainfall), and not yet with high degrees of certainty regarding changes in variability, which are often more important in hydrology than changes in magnitude, or on more relevant local (vs. global) change, although all these uncertainties are gradually being reduced (IPCC, 2007a).

More specifically in hydrology there are further uncertainties, specifically

- stochasticity, i.e. the inherent unknowable randomness (e.g. of rainfall);
- ignorance, i.e. our still imperfect knowledge of hydrological system dynamics; and
- scaling issues, e.g. on
  - spatial upscaling of process representations from points where measurements are made, to homogeneous landscape elements such as the hydrological response unit (HRU) in hydrology, to the 3-dimensional representation of a hillslope or small catchment, to disaggregated catchments (such as the Quinary Catchments in southern Africa), to regional sub-delineations (such as the Quaternary Catchments), to larger, often sub-continental scale international basins and, finally, to global scale representations, for example, at the scale of the perturbations associated with the El Niño-South Oscillation phenomenon; and equally on (Schulze, 2005a),
  - climatic downscaling of GCM information to regional climate change manifestations, which include local topographic forcing and, eventually, to the scales at which hydrological models operate, which is usually at the daily time step and at the Quaternary Catchment and, ideally, the Quinary Catchment spatial scale (Schulze, 2005a).

In regard to issues on climate change and hydrology it may also be argued that

- hydrological modelling (through incomplete process representations) and hydraulic design are, at best, still only approximations, with safety factors often built in, or that
- Africa has more pressing water problems than those related to climate change, or that
- impacts of the water engineered landscape (e.g. irrigation, channel modifications, water storages/releases or interbasin transfers) are generally greater than those of land use changes (e.g. afforestation or urbanisation) which, in turn, can be greater than those resulting from climate change (Schulze, 2001), but with a high dependence on the scale at which the water resources are managed.

Despite the uncertainties which abound, there are sound reasons to adopt a no-regrets approach to the potential hydrological impacts of climate change, because hydrological structures

- have long lead times from the planning to the operational phases,
- 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 (Schulze, 1997).

Furthermore,

- since the hydrological system amplifies any changes in rainfall, 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 decisions on water structures now, and for local hydroclimatic conditions, and cannot stall decisions until more certainty is available on climate change (Schulze, 2003).

To ignore the need to adapt to possible impacts of climate change on hydrological responses is, therefore, done at ones‘ own peril.

ii. What General Observations can be Made on Water Resources Management and Climate Change: Experiences from the "Thukela Dialogue"

The Thukela Dialogue was one of 17 national, basin and regional "dialogues" commissioned globally by the International Dialogue on Water and Climate (DWC) in seeking to bridge the information gaps between the water and climate sectors and so improve our capacity to cope with, and adapt to, the impacts on water management of increasing climate variability and change. Held in South Africa, and with a strong regional flavour, it nevertheless brought to the fore important general findings relating to adaptation strategies in the water sector which were captured by Schulze (2003) and are summarised in a wider African context below:

Water resource management (WRM) is not an end in itself. Rather, in an African context, it is a tool for equitable and sustainable social and economic development, thus is seen as a service to ones nation and its people, and as a tool with knock-on effects on all sectors of society (Rowlston, 2003). Climate change merely adds another layer of complexity to an already complex management of water resources. However, water managers need quantifiable information with which to

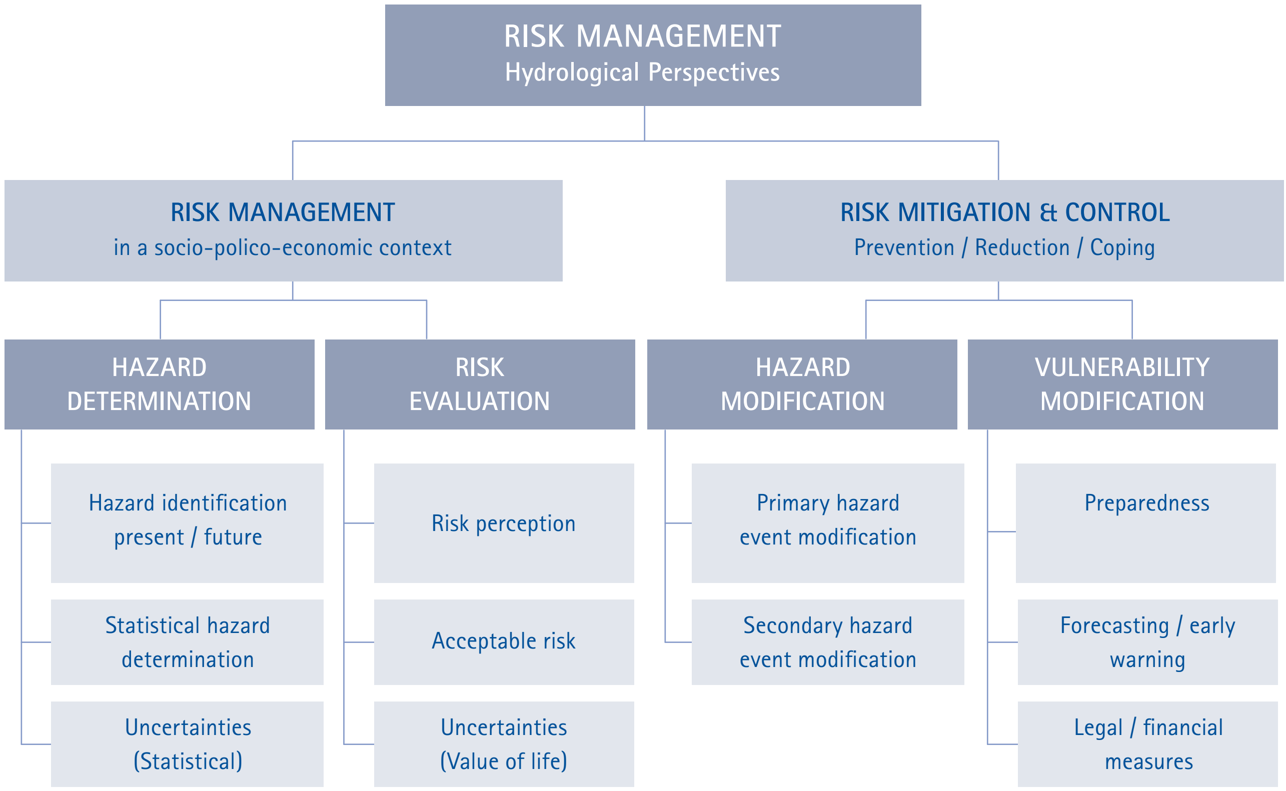


Figure 2.19: Risk management

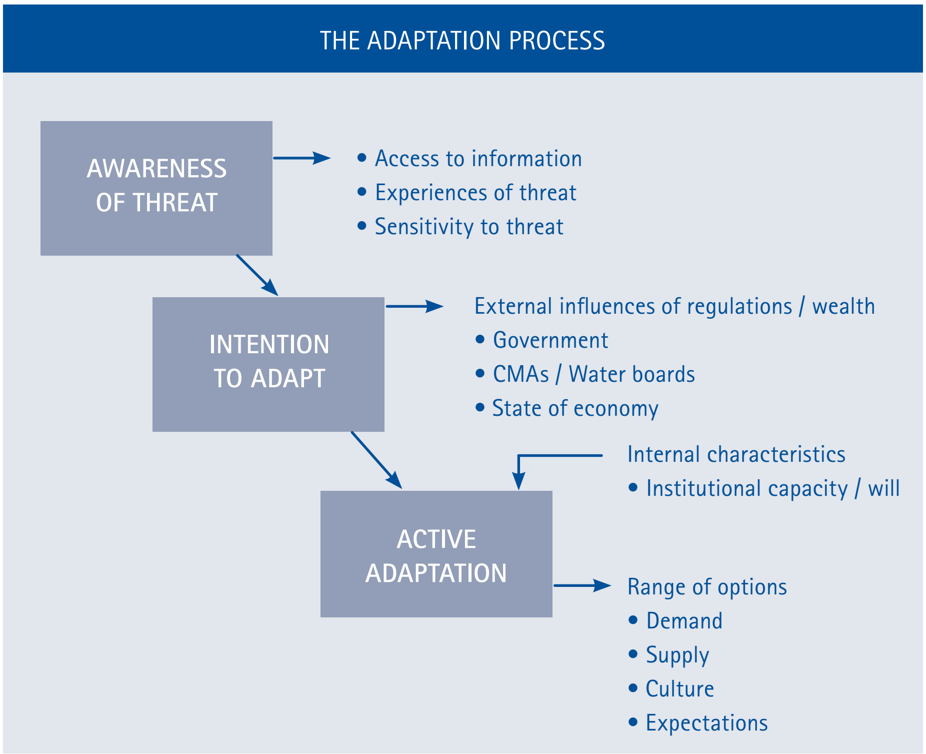


Figure 2.20: The adaptation process

make decisions, and not merely vague projections. Therefore, two clear requirements are for increased skills and quantification of uncertainties from the GCMs of future possible climates (Rowlston, 2003).

WRM does, however, already need to consider on how best to react to the still relatively low skills projections from GCMs and how best to use them in cost-effective contingency planning. Not only magnitudes and directions of climate change need to be known, but also when, where and how national departments of water affairs should start to apply their WRM strategies when bearing climate change in mind (Rowlston, 2003). The effects of climate change, and compensating for it, will have to be built into the full water management cycle. These effects include a more complete conceptualisation than that at present of the non-linearities in the different hydrological zones in ones country, in which the interactions of a changed climate will vary in their sensitivity and be dynamic (Schulze, 2003). Further, consideration should be taken of, for example, the implications of climate change and water licensing based on streamflow reduction impacts (partly because the distributions of natural baseline land covers against which land use impacts are assessed will change, and partly because land uses per se will undergo geographical shifts), or alterations to reservoir operating rules under changed climatic conditions.

It is important to place groundwater on the agenda when climate variability and climate change are being considered because of its potential value in future water resource management. Changes in climate will affect both ground- and surface water resources through changes in primary rainfall/runoff/recharge responses. However, there will also be additional changes on secondary effects on groundwater through changes in vegetation, land use and rates of evapotranspiration (Cavé et al., 2003). Amongst the biggest challenges for groundwater hydrologists in light of climate change will be improvements to overall water management, including the conjunctive use of surface- and groundwater and the use of groundwater as a back-up to systems dependent on surface waters, as well as improving methods for managing and controlling possible declines in the water table through artificial groundwater recharge (Cavé et al., 2003). An important consideration in light of climate change is that groundwater smoothes the short term variations which occur in surface water responses because of the delayed lag in its response to individual rainfall events and thus, unless it is already being overexploited, it can provide a reliable buffer to short term changes in rainfall patterns (Cavé et al., 2003).

From a design engineering perspective climate change is highly challenging in an African context, particularly in light of generally declining hydrometeorological networks and because the accuracy of computations on extreme events is a function of the quality, period and length of the records; much of which is lacking in Africa. Already the variability in the range of hydrological extremes in much of Africa is high, with some areas more vulnerable than others, and these patterns are likely to change. Furthermore, spatially the return periods of rainfall and runoff do not coincide (mainly as a result of differences in soils, land uses and/or antecedent soil moisture conditions within a catchment) and such spatial "discrepancies" could well become more complex with climate change (Smithers and Schulze, 2003). Many further questions on design hydrology arise with climate change, e.g. whether extremes are already becoming more extreme and more frequent; how one handles outliers of extreme events (which under present climatic conditions already pose serious problems in analysis); whether the frequencies of different types of extreme weather events (e.g thunderstorms vs tropical cyclones) are likely to change, such that the 15-year return period may shift to becoming the 5-year return period because a different type of rainfall is occurring. Furthermore, how does the design engineer factor the above issues into the present designs of structures which are built to last well into the era of predicted climate change? (Smithers and Schulze, 2003). Design hydrology will, therefore, have to be re-evaluated in the light of climate change and the anticipated enhanced climatic variability associated with this change.

In regard to policy and legislation links to future changes in climates, present legislation in most countries already contains sound principles on coping with the vagaries of inter-annual variability of climate and the hydrological amplifications thereof. The prospect of climate change, however, makes it more important than ever to apply the present legislation on water, conservation or mountain catchments more intensely, more timeously, at more locations and with more focus (Rowlston, 2003). However, a more direct adaptation of policies, strategies and legislation may still be required as a result of the strong likelihood of climate change. Care will nevertheless need to be exercised to ensure that certain adaptation options to climate change, such as water detention in situ on the catchment or planning new irrigation projects, do not run counter to certain current water policies on, for example, streamflow reduction or environmental flow requirements, and an integrated research effort will be required on adaptation (Rowlston, 2003). A special focus is required on the adequacy of government policies on water and disaster management in regard to the rural poor.

Under non-stationary climatic conditions, monitoring is becoming more important than ever, for not only are networks in Africa often sparse, and/or on the decline, and/or the data are of inadequate quality, but present baselines (i.e. benchmarks) against which future changes are quantified need to be established, not only in hydrometeorology, but also for agriculture and other land uses. There is thus a renewed need to monitor where we go from here into an "uncharted" climatic environment (Schulze, 2003).

In regard to agriculture and water in a climate change context, important water related legislation and policy revolving explicitly and implicitly around agricultural land already exists in many countries, e.g. legislation on streamflow reduction activities, on licensing for irrigation, water allocation, riparian zone clearance of aliens or on soil conservation. This confirms that the dynamic interrelationship between water and agriculture under present climatic conditions is already a highly symbiotic one, with any climatic driven impacts on changes in water availability in the soil as well as in the channel affecting agricultural practices and production (e.g. dryland crop yields, irrigation water supplies), while simultaneously any impacts of climate on agricultural practices and production affect water availability (e.g. water use by production forests; Schulze, 2003).

With respect to issues of the environment and climate change, the most critical ecological issue is the maintenance of biodiversity. This has implications in catchment management, both terrestrially and in-channel, which should be researched as an integrated whole, rather than pitching the various issues against each other. There is, as yet, only a very limited understanding of the full impacts of climate change on, for example, aquatic habitats, wetlands functioning or estuaries, or of ecosystem goods and services, with little knowledge as to whether, when and where certain thresholds of tolerance are exceeded in the various environmental systems. From an environmental perspective the effects of climate change will be different terrestrially vs in-stream. One reason is that the many and significant inter-basin transfers and other in-channel systems such as dams, have changed in-stream characteristics quite markedly, additionally, terrestrial hydrological responses, where irrigation is a major water user, have changed. Both terrestrial and in-stream responses will be very different under climate changed conditions (Schulze, 2003). The method of determining the environmental flows of water in streams for maintenance of downstream aquatic integrity by, for example, mimicking near-natural flow regimes to include minor and major floods, flow durations etc. under "average" and "drought" conditions will need to be reviewed to take into account possible effects of climate change for, if nothing else, climate change will result in new intra- and inter-seasonal equilibria of flow and sediment regimes, and therefore of new dynamic baseline conditions.

b. A Framework for Water Sector Adaptation to Climate Change: The Case for Assessing Secondary and Tertiary Impacts

As a point of departure from this topic, core reasons for adopting an appropriate adaptation strategy remain those of the IPCC's six statements in their 2001 report (IPCC, 2001), viz.

- Climate change cannot be totally avoided;
  - Anticipatory and precautionary adaptation is more effective and less costly than forced, last-minute, emergency adaptation or retrofitting;
- Climate change may be more rapid and more pronounced

ADAPTATION ISSUES AND THE WATER SECTOR . . . AT A GLANCE

Too Much Water, too Little Water

- Are recent floods / droughts signs of CC?
- Impacts will be on water quantity and quality; magnitudes and timing
- Uncertainties exist, but enough is known for action

Sectoral and Regional Aspects

- Water is a core sector, cascading to
  - agriculture
  - health
  - recreation
  - fisheries
  - navigation
  - biodiversity

Imbedding Adaptation

- Climate change needs to be integrated
  - agriculture
  - land use development
  - tourism
- We want win-win solutions with other benefits
- Achieve frameworks which are
  - cost effective
  - flexible
  - modifiable

Time and Multi-Stakeholder Dynamics

- Strategy implementation takes time
- Adaptation interactions are
  - international
  - national
  - provincial
  - local
- Have to involve
  - business
  - civil society

National Practices

- Need national policy frameworks on CC
  - long term planning
  - policy research
  - institutional development
  - infrastructure investment
  - education
  - information exchange

Research and Policy Support

- Need local scenarios
- Need 20 year timeframes
- Reduce uncertainties
- CC vs CV
- Couple climate with hydro models
- Maintain networks
- Vulnerability research
- Ecosystems research

Figure 2.21: Adaptation issues and the water sector . . . At a glance (EEA, 2007)

than current estimates suggest, with unexpected events possible;
  - Immediate benefits can be gained from better adaptation to climate variability and extreme atmospheric events;
  - Immediate benefits also can be gained by removing maladaptive policies and practices; and
- Climate change brings opportunities as well as threats, with future benefits also resulting from climate change (IPCC, 2001).

On a more local front, it was again the "Thukela Dialogue" (Schulze, 2003) which highlighted numerous key points on adaptation:

- First, it needs to be reiterated that while many sectors in South Africa are vulnerable to the effects of climate change, the water sector is arguably amongst the most vulnerable. Furthermore, hydrological responses to climate change may be regarded as an integrator among the many sectors dependent upon, or affected by, the spatio-temporal distribution of water, e.g. rainfed agriculture, irrigated agriculture, the insurance industry, the transport industry, disaster management, rural/community health, or industrial development (Rowlston, 2003).
- Questions which arise from the above include the following:
  - What mechanisms exist within central, provincial or local government to co-ordinate the various responses to climate change?
  - What mechanisms are in place to prevent a particular sector from adopting a climate change related strategy which may be of short-term benefit to that sector, but be detrimental to other strategies, or in the national interest?
- In adopting adaptation strategies for South Africa, scien-

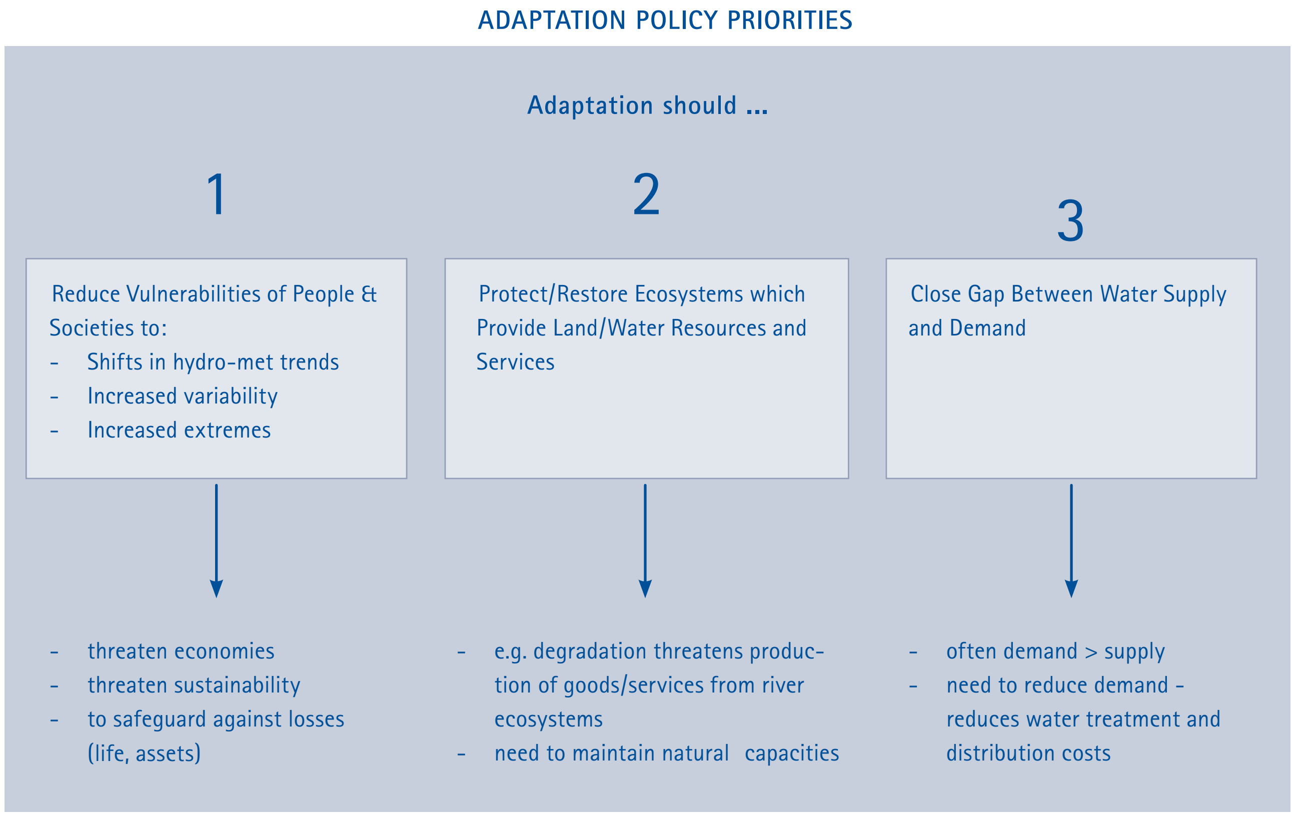


Figure 2.22: Adaptation policy priorities (Bergkamp et al., 2003)

tists and government need to move from only considering primary impacts of climate change to placing far more emphasis on modelling secondary and tertiary effects on hydrology (Schulze, 2003):

– Primary impacts of climate change on hydrological responses focus, for example, on changes in total/averaged flows, e.g. MAR.
– Secondary impacts still deal only with fluxes of water per se, and would consider, inter alia, modelling 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 and intra-annual time scales, effects of changing vegetation dynamics on resultant hydrological responses, regional amplification of variability, persistencies of flows above or below selected thresholds, changes in the magnitudes and frequencies of extreme events related to both floods and droughts, including peaks over threshold analyses, changes in groundwater recharge, or effects of land use on water availability, mainly through alterations in the partitioning of rainfall into stormflow and baseflow (Schulze, 2003).
– Tertiary (higher order) impacts of climate change go beyond fluxes of water per se to include assessing changes in water quality (for example of sediment yield; water chemistry, i.e. N, P or salinity; or biological status of water using E.coli as an indicator), or of water temperature (as a driver of changes to aquatic habitats or of water-borne diseases), and consequences thereof in purification costs or human health, as well as changes

in aquatic ecosystems and effects of climate change on ecosystem goods and services or on in-stream flow requirements (Schulze, 2003).

- Furthermore, climate perturbations, responding 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 problems for the poor, who often live either on floodplains which may become more prone to flooding in the future, or alternatively, live along higher lying watershed boundaries where streams tend to be more ephemeral and may become even more so in future (Schulze, 2003).

c. A Framework for Water Sector Adaptation to Climate Change: The Example of South Africa

An initial framework of needs and requirements when planning strategies to cope with, and/or adapt to, impacts of anticipated climate change and potentially enhanced climate variability has been developed for South Africa following a series of workshops with water resource managers, water policy makers, consultants, agricultural experts, environmentalists, socio-economists and other scientists (Schulze, 2005a). It consists of a matrix of

- three time frames of change, viz.
  - long term strategic, i.e. decadal, such as climate change;
  - medium term tactical, i.e. seasonal, such as a forecasted drought; and
  - short term operational, such as flood events/disaster management

  versus
- three sets of needs and requirements, or instruments of coping, viz.
  - legal and policy;
  - institutional and management; and
  - information, research and monitoring.

For the long term strategic decision time frame involving climate change the following were highlighted (Schulze, 2005a; Table page 69-70):

- On Legal and Policy issues a strong focus was placed on
  - rendering the National Water Resource Strategy more climate change “aware” than it was at present, and also more specific in regard to climate change, as well as
  - emphasising more strongly effective risk management policy.
- On Institutional and Management needs and requirements in regard to adaptation to climate change, the foci were
  - effective operations of Catchment Management Agencies, for them to take cognisance more seriously of climate change,
  - risk management,
  - governance, and
  - enforcement of existing policies.
- On Monitoring, Research and Information needs to be considered in light of projected CC impacts on the water sector, issues highlighted included
  - a review of hydrometeorological networks in South Africa in light of detecting impacts of climate change which may already be present,
  - the availability of quality data,
  - building capacity in the field of climate change studies,
  - improving both the climate and hydrological models used in impact studies, and
  - educating, training and communicating with relevant targeted groups (e.g. politicians) on climate change issues (Schulze, 2005a).

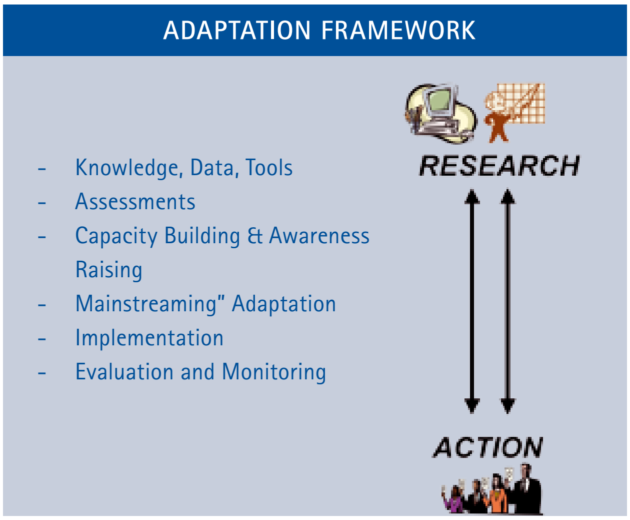


Figure 2.23: Adaptation framework

Legal and policy

International

- Mobilise the implementation of the Kyoto Protocol in southern Africa
- Re-negotiate international water agreements with neighbouring states in light of Climate Change (CC)

National Water Resource Strategy

- NWRS must recognise the importance of CC and cater for it more explicitly
- NWRS needs to be updated routinely to address new finding on CC impacts
- NWRS needs to be provided with more “teeth” re. CC
- More co-participation required in the NWRS with political, social and economic sectors
- NWRS needs to define clearly the boundaries of accountability and responsibility between
  - national
  - CMA/WMA
  - District Municipality and
  - city specific issues

National Climate Change Response Strategy (NCCRS)

- Department of Environmental Affairs and Tourism (DEAT) needs
  - a more strategic approach to CC
  - greater commitment to apply the NCCRS
  - to develop more specific legislation re. CC

More Specific Policy Requests/ Requirements

- Re. Risk Management
  - review existing national disaster management legislation re. CC, e.g. fires, floods, droughts
  - floodplain zoning and management; spatial considerations; urban areas
  - dam safety and spillway standards
  - property risk policies re. predicted floodlines with CC
- Legislate more specifically on demand management
- Develop a policy on long-term hydrometeorological monitoring

Enforcing/Policing policy

- Enforce existing policies more effectively

Institutional and management

Catchment Management Agencies (CMAs)

- Establish CMAs which will operate effectively re. Integrated Water Resources Management (IWRM), including CC
- Improve co-ordination within and between CMAs re. activities, methodologies
- Ensure wider stakeholder participation

Risk Management

- Revise/improve risk management (RM) plans re. floods, droughts
- Set up an advisory to advise land owners in flood prone areas re. risks, flood probabilities
- Implement a State insurance scheme for disasters
- Develop policy on water restrictions

Governance

- Establish incentive schemes for initiatives in co-operative governance
- Ensure that institutions adapt to CC findings at all levels of government and the private sector

Infrastructure

- Need improved strategic plan for new infrastructure re. WRM
- Construct more dams in relevant areas to make provision for additional water needs with CC
- Review systems operations re. assurance of supply

Water Licensing

- Exercise more care in evaluating/awarding of licences to water users in light of CC
- Raise tariffs to fund effective IWRM

Enforcement/Compliance

- Enforce compliance with regulations/laws
- Increase enforcement re. controlling groundwater abstractions

Monitoring, research & information

Monitoring

1. Networks & General

- Revise the entire network of rainfall and streamflow gauges re. detection of CC, and adapt, if necessary
- Identify and maintain high quality flow gauges
  - with long records
  - on unaltered catchments
- Measure streamflow at all strategic points
- Improve monitoring of land use change
- Improve and regularly update WARMS database for better application in granting water use licences
- Create an independent Earth Systems monitoring agency for South Africa

2. Data

- Ensure integrity of streamflow data
- Achieve greater integration of hydroclimatic and related databases
- Make data more readily available
- Ensure transparency in sharing data

Research

1. General Capacity Building

- Build more capacity re. CC research
- Create incentives for new techniques in CC related water research

2. Climate Models

- Improve CC projections for SA, to increase confidence levels in their application to WR
- Improve downscaling techniques for application in SA

3. Hydrological Modelling

- Improve process representations in hydrological models for application in a range of hydroclimatic regimes (e.g. semi-arid zone)

4. Specific Research Requirements

- Climate change scenario analysis re. hydrological responses
- Regional impacts of CC on WR
- Storage of water in disused mines, aquifers
- Reducing evaporation from dams
- Forecasting of hydrological attributes (e.g. streamflow irrigation requirements) from near real time to days to seasons ahead with rapid dissemination of results
- Optimise crop selection according to climate forecasts
- Undertake baseline hydrological studies for use in impact studies (including control sites)
- Quantification of components of the hydrological cycle
- Identification of high-risk, vulnerable areas
- Surface water/groundwater interactions
- Explore deeper groundwater systems for emergency supplies in droughts
- Status of catchment soil moisture/vegetation using remote sensing
- Water demand patterns
- Alien plant control re. water use

Information

1. Education/Training

- Education of politicians and other decision makers re. CC and its impacts (awareness)
- Education in Earth System Science at high schools
- Training workshops based on latest findings of CC and WR

2. Communication

- Require an effective communication policy to be developed re. CC, including media, schools
- Improved communications between scientists, engineers and policy makers

Table 2.2: Needs and requirements with regard to adaptation to climate change in the South African water sector, as identified by stakeholders (Schulze, 2005a)

Many of the policy and management issues summarised in Table 2.2 are nothing more than putting into practice more effectively what is already on paper. Furthermore, a number of the research issues identified have in fact been, or are currently being, addressed in a number of research projects in South Africa.

d. Where to Now? Limits to Adaptation

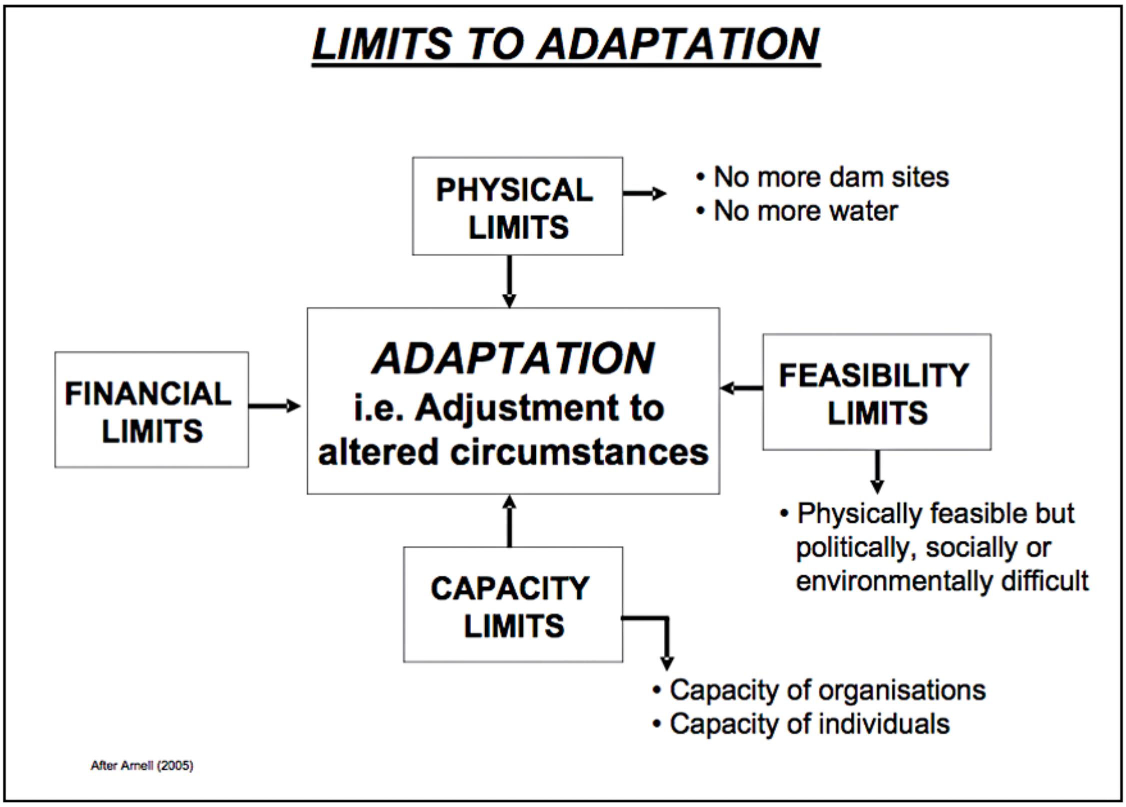
Clearly, planned adaptation is required in the highly sensitive water sector in addition to autonomous adaptation. Many workshops worldwide, as well as the findings of the IPCC (2007b), have signalled the water sector's awareness of a potential additional stress arising from climate change. A clear intention by stakeholders in the water sector to adapt is now required. Iindeed, the stage is now set for active adaptation to be implemented, through policy instruments and through implementation by practitioners operating at international and national levels, as well as at local levels.

There are, however, limits to adaptation which need to be appreciated (Figure 2.24):

- Nature sets physical limits, for example, by provision of a finite water resource, be it surface water and/or groundwater, in situ and/or transferred.
- The socio-economic and political scene, particularly in developing countries, sets other limits to adaptation which are usually government or governance related, be they
- financial constraints,
- feasibility limits, where adaptation options may be feasible, but are not effected because of country or region specific political, or social, or environmental pressures, or
- capacity limits, both within organisations in general and of individuals tasked with effecting adaptation policies on the ground (Figure 2.24).

Despite the logical appeal of, and belief in, whole catchment water management, initiatives in IWRM have often neither lived up to their expectations nor reputations (Frost, 2001). These problems are likely to be exacerbated by anticipated impacts of climate change and the associated uncertainties. Barriers to IWRM, particularly in LDCs but not exclusively so (as identified for example by Falkenmark et al., 1999; Frost, 2001; Schulze, 2001), should not, however, become barriers to timely and adequate adaptation strategies related to CC. Such barriers include the following:

- Sectoralism often exists within and between government departments, manifested by the fragmented nature of institutional structures, with often different functions and



After Arnell (2005)

Figure 2.24: Limits to adaptation (after Arnell, 2005)

political agendas in regard to climate change responsibilities where these link up with risk management, resource management or international water obligations.

- There is frequently a lack of clearly defined overall climate change related strategies in the water sector, including management objectives and mechanisms for delivery, and there is a tendency for being “high on rhetoric and talk” at the strategic level, but “low on action” on the ground.
- Water in a future climate is often viewed as a potential source of conflict, not only between sectors (e.g. agriculture vs urban demands), but also within a sector (e.g. dryland vs. irrigated or commercial vs. subsistence agriculture water needs), and in particular with respect to the right to water, and tensions between upstream vs. downstream water users and uses. The latter is a special concern in the interactions between IWRM and climate change because of an inherent “asymmetry” (Frost, 2001) in the interactions, where
  - downstream users are affected by direct upstream responses to CC, e.g. through changes in abstractions, impoundments, flow reductions through intensification of agricultural land uses and/or deterioration of water quality, while
  - upstream users can only be affected by downstream users indirectly by political pressures on future water uses, legislation or compensatory payments/levies for ecosystems goods and services.
- Deficiencies in research, and hence information, pertaining to CC related impacts and vulnerabilities, frequently exist as a result of the application of outdated climate scenarios, inadequate downscaling and use of inappropriate models, insufficient spatial information, a lack of willingness among organisations to share data and information and/or networks of information flows being inadequate.
- Deficiencies are evident in capacity with regard to effecting the integration between climate change and water resource management.
- Deficiencies come to the fore in understanding adequately the dynamics between land management and climate change, including how the use of land impacts on the quantity and quality of water, but more specifically on how to cope with/adapt to changing hydrological conditions with respect to inter-annual climate variability or more permanent climate change;
- Deficiencies are frequently evident in water management options under future climatic conditions, in regard to its storage, treatment, equitable allocation and distribution as well as best practice in implementing demand management.
- Deficiencies occur in stakeholder involvement, e.g. with unstructured approaches to public consultation in regard to CC, a lack of trust between CC scientists and stakeholders, often centred around issues of uncertainties of what the future may bring (and when), or the presence of strong pressure groups and lobbies.

IWRM aims at finding long term sustainable ways to cope successfully with the particular environmental pre-conditions in a certain region, while simultaneously satisfying societal needs by balancing different functions of water (now and in future) with different sectors (e.g. environmental, agricultural, industrial) and stakeholder groups, who may range from policy makers to local landowners (Falkenmark et al., 1999). One of these environmental preconditions is in the realm of climate and by implication, therefore, climate change. Climate change introduces new players to water management (e.g. climatologists, adaptation strategists) as well as new dimensions (e.g. non-stationary climate baselines, uncertainty analysis). Implicitly and explicitly the impacts of climate change transcend virtually all facets of IWRM shown in Figure 2.2, and particularly in LDC situations, be they from a water demand vs. supply perspective, or from an in-stream vs off-stream ecological focus, or from an institutional/governance angle.

Within the water sector, IWRM presents itself as a sound conceptual and practical medium with which to embrace the additional stressor which impacts of climate change present. Despite its shortcomings, IWRM provides a framework within which to research and evaluate a range of policy and practical choices for adaptation and it offers the opportunity to assist in assessing the risks and options of environmental, social and economic policy makers by re-connecting people to water issues within their catchment through consultative processes, stakeholder participation and partnership options in an uncertain future.

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