

UPDATE OF POTENTIAL CLIMATE CHANGE IMPACTS ON RELEVANT WATER RESOURCES RELATED ISSUES IN THE UMGANI AND SURROUNDING CATCHMENTS USING OUTPUTS FROM RECENT GLOBAL CLIMATE MODELS AS INPUTS TO APPROPRIATE HYDROLOGICAL MODELS

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CHAPTER 1 SETTING THE SCENE

Water resources planning involves long term decisions to be made, with hydraulic infrastructure usually designed to operate for 30 to 100 years into the future – well beyond the time frames of climatic stationarity where one assumes that one can plan and design infrastructure on the basis of past climatic and hydrological experiences. Observed increases in CO₂ emissions into the atmosphere from industry (**Figure 1.1** left) and associated rising trends in temperatures are already being observed (**Figure 1.1** right). This trend is projected to continue into the future. With the shifts associated with those observations in regards to changing atmospheric dynamics and, consequently, to changes in spatial and temporal rainfall and hence runoff patterns into the future, climate change has become an imperative to consider in water resource planning.

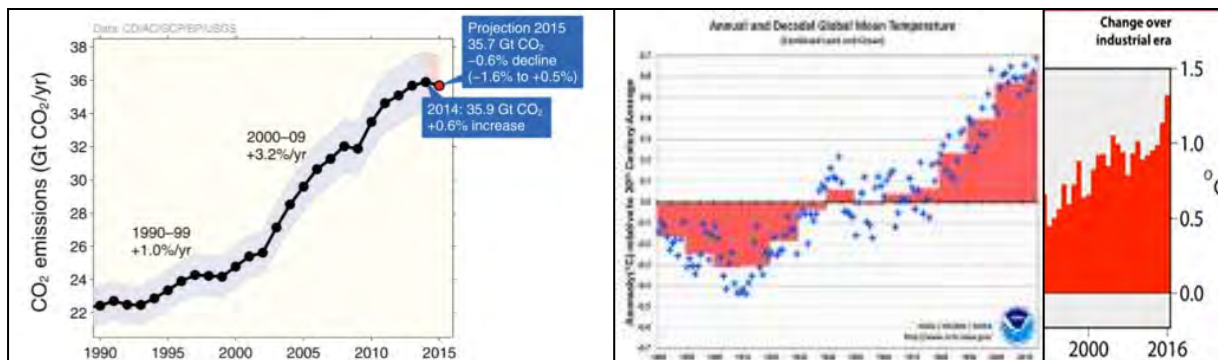


Figure 1.1 Recent CO₂ emissions from industry (left) and (right) observed annual and decadal temperature increases (Source: NOAA, 2016)

Numerous reports on climate change and water related outcomes which have included the area of interest of Umgeni Water have been completed in recent years. These include major Water Research Commission funded reports of 2005 and 2012 (Schulze, 2003; 2005; 2012) covering the entire South Africa, a more recent GIZ funded study on climate change risk and vulnerability assessments for the nine Water Management Areas covering the country (Schulze and Davis, 2018), the hydrological component of the Durban Climate Change Strategy (Schulze, 2014; Schulze and Davis, 2014), the KwaDukuza Climate Change Strategy (Schulze, 2013), as well as in-house studies within Umgeni Water. All except the 2018 report were based on previous generations Global Climate Models (GCMs).

This Report is an update of, and an expansion on, previous work covering Umgeni Water's area of interest, and it is based on outputs from selected GCMs from the most recent so-called CMIP5 GCMs.

The report consists of 11 chapters covering, beyond this introductory chapter, ones on

- The location of the Study Area;
- Tools used in this Study;
- Potential evaporation and projected changes;
- Rainfall and projected changes;
- Dry spells and projected changes;
- Wet spells and projected changes;
- Streamflows and projected changes;
- Design rainfall and projected changes;
- Design streamflows and projected changes; and
- Concluding thoughts,

with each of the technical chapters also including a concluding section on possible implications to Umgeni Water.

CHAPTER 2 LOCATION OF STUDY

This Report covers the catchment of the Umgeni and surrounding catchments of interest to Umgeni Water along the eastern seaboard of South Africa in the Province of KwaZulu-Natal, one of the nine provinces of South Africa (**Figure 2.1**). The area of interest is located between 28°45' and 30°10'S and between 29°20' and 31°30'E (**Figure 2.2**) and ranges in altitude from sea level to nearly 3 000 m in the Drakensberg in the west. Its location in relation to the other provinces of South Africa is shown in **Figure 2.1** and some of the major towns and villages are shown in **Figure 2.2**.

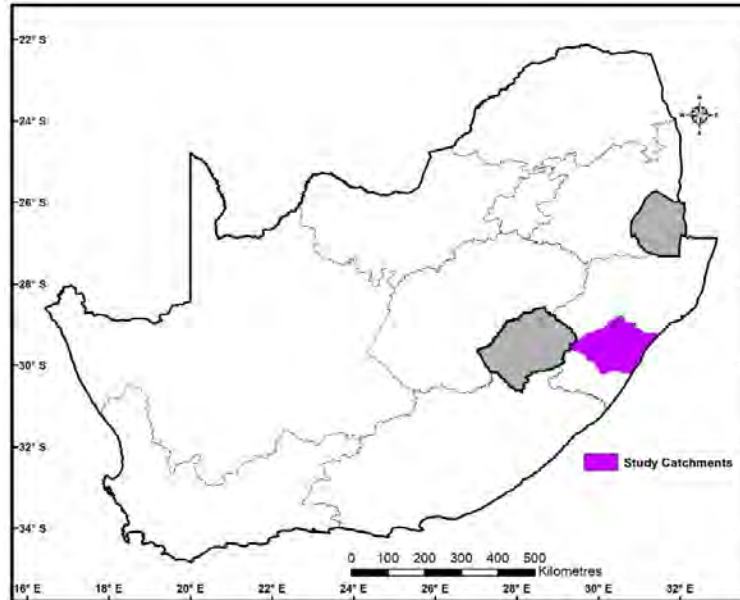


Figure 2.1 Location of the Study Area within South Africa

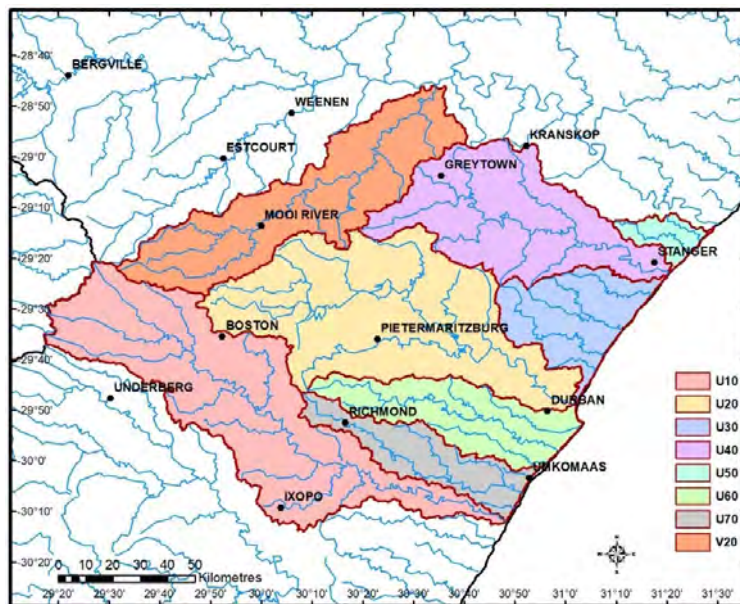


Figure 2.2 Tertiary catchments, main towns and major rivers of the Study Area

The Tertiary catchments named by the main river, the Quaternary catchments within the Tertiaries and the Quinary catchment numbers from the South African Quinary Catchments Database (Schulze *et al.*, 2010) as well as the number of Quinaries considered in this Study are given in the table below, with a total of 177 Quinary catchments making up the Study Area.

Tertiary Catchment	Quaternaries	Quinary Range	No. of Quinaries
Mgeni	U20A – U20J	4672 – 4707	27
Mooi	V20A – V20K	4904 – 4935	36
Mlazi	U60A – U60F	4753 – 4770	18
Mkomaas	U10A – U10M	4636 – 4671	36
Illovu	U70A – U70E	4771 – 4785	15
Mvoti	U40A – U40J	4723 – 4749	27
North Coast 3 Rivers	U30A – U30E	4708 – 4722	15
Small Others	U50A – U50C	4750 – 4752	03
Total Quinaries			177

The discretisation of the Study Area into Tertiary catchments (in red), Quaternaries (in green) and Quinaries (in grey) is shown in **Figure 2.3**.

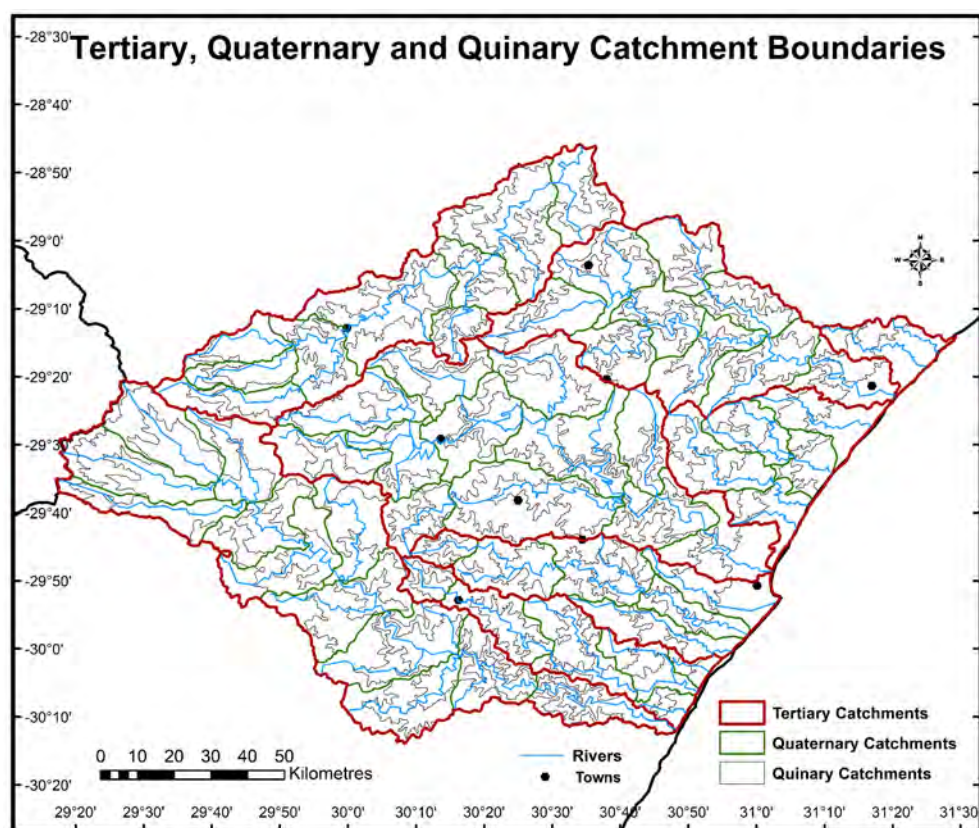


Figure 2.3 Discretisation of the Study Area into Tertiary catchments (in red), Quaternaries (in green) and Quinaries (in grey)

CHAPTER 3 TOOLS USED

Mapping Within the Study Area at a Spatial Resolution of Quinary Catchments

Maps shown in this Report have been prepared at a spatial resolution of so-called Quinary catchments, QCs (Schulze and Horan, 2010), shown previously for the Study Area in **Figure 2.3**. QCs constitute a three-fold sub-delineation of Quaternary catchments, delineated with a 90 m DEM by natural breaks in altitude within Quaternary catchments by a technique known as Jenks' optimisation within ArcGIS, and as such these polygons of unequal area are relatively homogeneous hydrological (and agricultural) spatial units in regards to climate, topography and soils. Within a Quaternary the Upper Quinary (UQ) discharges into the Middle Quinary (MQ) and that into the Lower Quinary (LQ) with that, in turn, discharging into the LQ of the next downstream QC, as shown in **Figure 3.1**. The reason for this is that the UQ and MQ of the immediate downstream QC may be at altitudes higher than that of the stream exit of the upstream QC. In total 5 838 Quinaries were thus delineated within South Africa, Lesotho and Swaziland, of which 177 make up the Study Area of this Report.

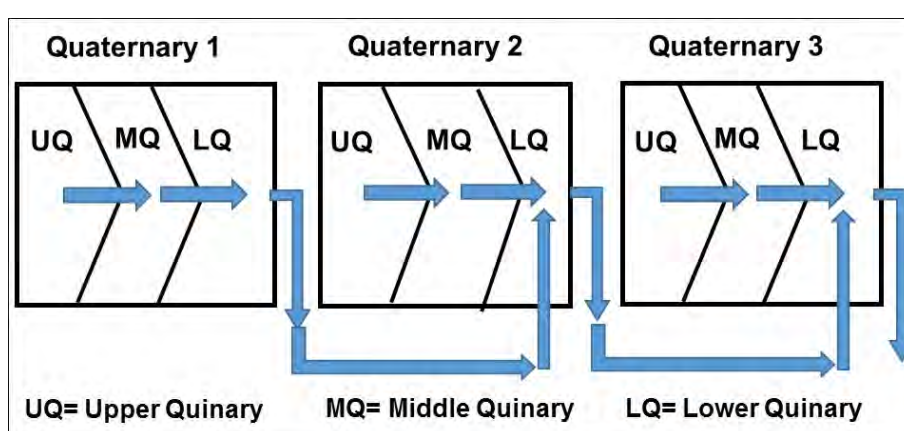


Figure 3.1 Quinary catchments flowpaths among and between Quaternary catchments

The Database of Historical Climate

The historical climate of the Study Area, be it used for assessments of direct variables of climate such as rainfall or for indirectly computed variables such as streamflow, provides the reference climate, or baseline, against which projected impacts of climate change can be evaluated. Some details of the historical climate database are given below.

Rainfall

In South Africa, rainfall is considered the most important input into any hydrological assessment model. A comprehensive database of quality controlled rainfall data in southern Africa was compiled by Lynch (2004). From that database, a rainfall station, termed the “driver” station, was selected for each Quaternary catchment. Each driver station contained a 50 year record of daily rainfall from 1950 to 1999. The selection of driver stations was followed by the determination of multiplicative month-by-month rainfall adjustment factors (from 1 arc minute rasters of median monthly rainfalls created by Lynch, 2004) for each Quinary and these were then applied to the driver station’s daily records in order to render its daily rainfall more representative of that of the Quinary. This resulted in a unique 50 year daily rainfall record for each of the 177 Quinaries covering the Study Area.

Temperature and Temperature Derivatives

Daily maximum and minimum temperature values facilitate estimations to be made, either directly or indirectly, of solar radiation, vapour pressure deficit and potential evaporation (Schulze, 2008). Procedures outlined by Schulze and Maharaj (2004) enable the generation

of a 50 year historical time series (1950-1999) of daily maximum and minimum temperatures at any unmeasured location in the Study Area at spatial resolution of one arc minute of latitude / longitude (i.e. $\sim 1.7 \times 1.7$ km). At each of these grid points the maximum and minimum temperatures were computed for each day of the 50 year data period from two selected, independent temperature stations and by use of regional and monthly temperature lapse rates. At each grid point the daily values derived from these two stations were then averaged in order to modulate any biases emanating from either of the two stations' generated records (Schulze *et al.*, 2010). Excellent verifications of results from this methodology were achieved (Schulze and Maharaj, 2004). The resulting 50 year time series of daily maximum and minimum temperatures was then used to generate daily estimates of solar radiation and vapour pressure deficit for each Quinary, details of which are described in Schulze *et al.* (2010). From these, daily values of reference potential evaporation were computed.

The Global Climate Models (GCMs) Used in this Study

The suite of climate scenarios used in this Report were from the World Climate Research Programme sponsored Coordinated Regional Climate Downscaling Experiment, CORDEX, in each case with daily rainfall and maximum / minimum temperature given, with the latter used to derive daily values of solar radiation, relative humidity and potential evaporation. For these climate scenarios two 30 year periods were used, viz.

- 1976-2005 (termed the “historical” climate by CORDEX, but to avoid confusion, termed the “present” climate in this Report) and
- 2016-2045 (termed the “immediate future” in this Report).

For the immediate future scenarios, outputs from the “business as usual” Representative Concentration Pathway 8.5 were used, with the GCMs downscaled to the 5 838 Quinary catchments and then bias corrected for local topography by methods described in Schulze *et al.* (2014).

The GCMs used in this Report were

- CCCma-CanESM2_historical_RCA5_1976
- CCCma-CanESM2_rcp85_RCA5_2016
- CNRM-CERFACS-CNRM-CM5_historical_RCA5_1976
- CNRM-CERFACS-CNRM-CM5_rcp85_RCA5_2016
- ICHEC-EC-EARTH_historical_RCA5_1976
- ICHEC-EC-EARTH_rcp85_RCA5_2016
- NCC-NorESM1-M_historical_RCA5_1976
- NCC-NorESM1-M_rcp85_RCA5_2016
- NOAA-GFDL-GFDL-ESM2M_historical_RCA5_1976
- NOAA-GFDL-GFDL-ESM2M_rcp85_RCA5_2016

These climate models are also referred to as the CMIP5 GCMs.

The ACRU Hydrological Simulation Model (Schulze, 1995 and updates)

Background 1: The Use of Models to Evaluate Hydrological Responses

Long term observations of hydrological responses such as stormflow or baseflow or sediment yield, as well as of transpiration from plants or evaporative losses from the soil surface, at the scales of homogeneous response areas such as Quinary catchments cannot be made for all feasible combinations of climate, soils, land uses and their different management regimes for reasons of logistics, time and cost. In order to mimic such responses, an appropriately structured and conceptualised hydrological simulation model has to be used. Such a model is thus viewed as a tool for transferring knowledge (i.e. observation > analysis > information > prediction) from a selected study site where observations are made (e.g. a research plot or catchment) to other unmonitored areas (e.g. a Quinary catchment) where the information is

required and hydrological decisions may have to be made. The model does this by simplifying a complex terrestrial system by way of a sequence of equations and pathways which describe the atmosphere-soil-plant-water continuum on the landscape component of the area (or catchment) and the flows and storages in the channel component of the catchment.

Background 2: From Model Input to Model Output

Such a hydrological model requires **input** of known, or measurable, or derivable factors made up of data and information on, *inter alia*,

- climate (e.g. daily rainfall, maximum and minimum temperature, potential evaporation),
- physiography (e.g. altitude, its range within a catchment, slope gradients),
- soils (e.g. thicknesses of the various soil horizons, as well as soil water retention at critical soil water contents and saturated drainage rates from the respective horizons, and/or the inherent erodibility of the soil),
- land uses (e.g. natural vegetation and crop types, levels of management, planting dates, growth rates, above- as well as surface and below-ground vegetation attributes at different growth stages during the year and for different management strategies / scenarios),
- soil water budgeting threshold and rates (e.g. onset of plant stress, degrees of stress, capillary movement),
- runoff producing mechanisms (e.g. stormflow generation, recharge and resultant baseflow rates, as well as flows from impervious areas),
- irrigation practices (e.g. crop type, above-and-below-ground attributes at different growth stages, modes of scheduling and their controls, source of water, application efficiencies) and, where relevant, information on
- dams (e.g. inflows, full supply capacities, surface areas, evaporation rates, releases, abstractions and inter-basin transfers), or
- other abstractions (e.g. domestic, livestock by amount, season and source of water).

This information is **transformed** in the model by considering

- the climate, soil, vegetative, hydrological and management *subsystems*
- how they *interact* with one another
- what *thresholds* are required for responses to take place
- how the various responses are *lagged* at different rates and
- whether there are *feedforwards* and *feedbacks* which allow the system to respond in a positive or reverse direction.

The model then produces **output** of the unmeasured variable to be assessed, for example,

- streamflow (i.e. the so-called “blue water” flows), from different pervious and impervious parts of the catchment, including stormflows and baseflows being modelled explicitly and on a daily basis, and hence high and low flows,
- evaporation (i.e. the so-called “green water” flows) from different parts of the catchment, and made up of productive transpiration through the plant plus the non-productive evaporation from the soil surface,
- irrigation water requirements (gross or net requirements; associated crop yields; deep percolation and stormflow from irrigated areas; water use efficiencies under different modes of scheduling water for irrigation; analysis of incremental benefit of applying irrigation vs dryland farming),
- peak discharge, and
- sediment yield from different parts of the catchment and computed on an event-by-event basis for the pertinent hydrological, soil, slope, plant cover and management conditions,

with all of the above output available as a

- risk analysis (month-by-month / annual statistics for median / mean conditions and for, say, driest / wettest years in 10 or 20 years; flow variability or extreme value analysis).

Concepts of the ACRU Model

The ACRU hydrological modelling system (Schulze, 1995 and continual updates) includes the facilities to simulate the hydrological responses described above, as well as others and, as a multi-purpose model (**Figure 3.2**) was selected as a suitable model for this Report. It contains options to output, *inter alia*, daily values of stormflows, baseflows, total streamflow, transpiration, soil water evaporation, peak discharge, sediment yields, recharge to groundwater, reservoir status, irrigation water supply and demand as well as seasonal crop yields at a specific location / catchment.

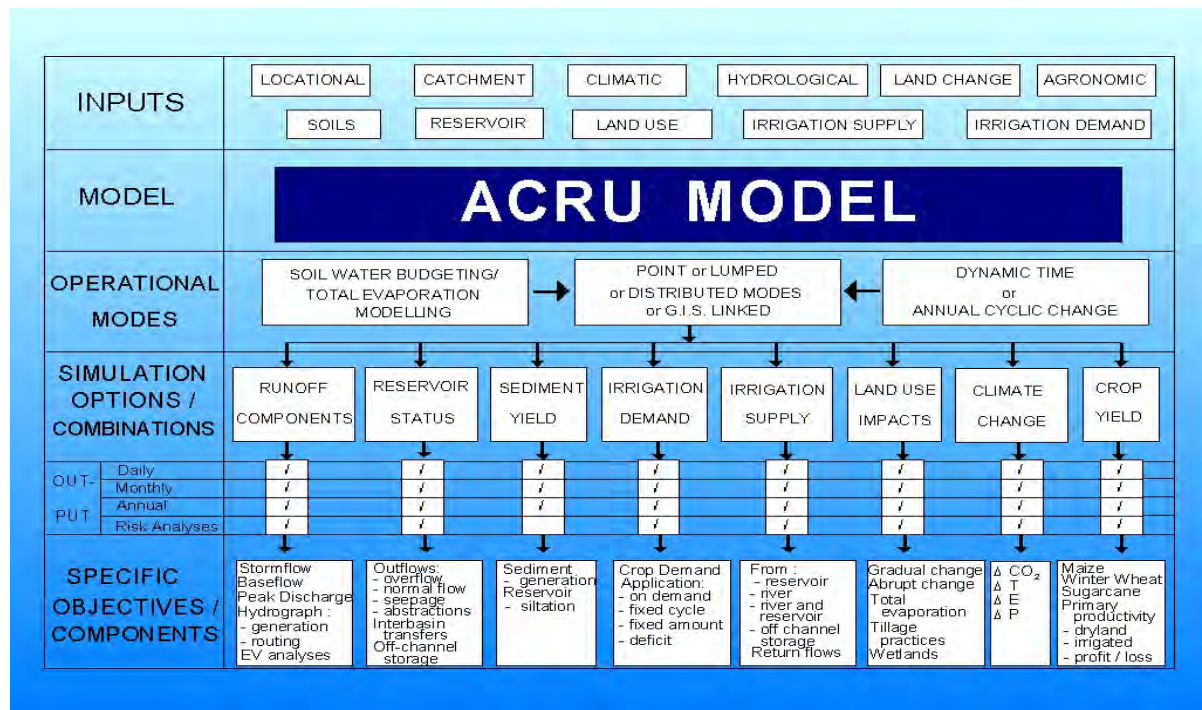


Figure 3.2 ACRU: Concepts of the multi-purpose modelling system (Schulze, 1995)

ACRU is a daily time step and physical-conceptual model. The model revolves around multi-layer soil water budgeting (**Figure 3.3**) and is structured to be sensitive to changes in land uses and management. Individual processes and equations are not given here, but can be read up in Schulze (1995).

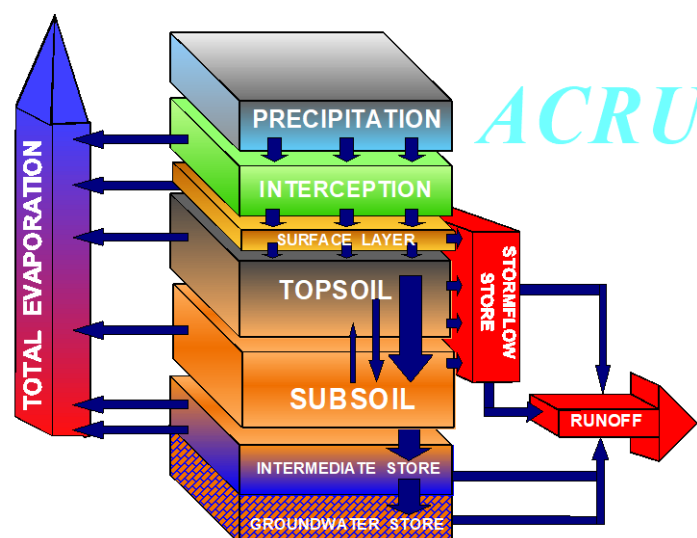


Figure 3.3 Structure of the physical-conceptual ACRU model (Schulze, 1995)

CHAPTER 4 POTENTIAL EVAPORATION

Some Concepts and Definitions around Evaporative Losses

The accurate estimation of evaporation from storage reservoirs, wetlands and rivers can constitute a major loss of water to water resource managers, irrigators and other downstream users. Similarly, evaporation from natural vegetation or agricultural crops is vital, because evaporation is the driving force of the total amount of water which can be "consumed" by a plant system through the evaporation and transpiration processes.

Evaporation is controlled by three atmospheric conditions, *viz.*

- the capacity of air to take up more water vapour (with this capacity increasing rapidly at higher temperatures and being determined also by the relative humidity, RH , of air - the lower the RH the more favourable the conditions for evaporation),
- the amount of energy available for the process of evaporation (with the energy provided mainly by solar radiation), and
- the degree of turbulence (related to wind) in the lower atmosphere (where the turbulence is necessary to replace the moist air layers above the evaporating surface with drier air from higher levels or from different air masses).

These three factors create an *atmospheric demand* and when this demand can be met fully, e.g. when soils are wet and actively growing vegetation covers the ground completely, then *potential evaporation* (E_p) takes place.

All three these factors change with global warming.

The actual amount of water "consumed" by a vegetated surface is termed *total evaporation*, E , and E may be taking place at potential rate (wet soil conditions) or at an *actual evaporation* rate which can either be equal to E_p or lower (the latter when soils dry out and plants are under water stress).

Estimating Potential Evaporation

There are many methods of estimating potential evaporation E_p . These range from complex equations to measurements from evaporation pans and simple equations based on single variables such as temperature. These methods all give slightly different answers under different climatic conditions, and a *reference potential evaporation*, E_r (with its inherent advantages and defects), therefore has to be selected. This reference is that evaporation against which results from other methods must be adjusted appropriately.

In this Report the Penman-Monteith method of estimating evaporation, E_{pm} , is used as the point of departure in computations (Penman, 1948; Monteith, 1981). The derivation of the relatively complex Penman-Monteith equation uses solar radiation, humidity, temperature and wind as its climate inputs and a version for South Africa can be found in Schulze and Kunz (2012). Daily values of Penman-Monteith E_{pm} were then multiplied by a local factor varying from 1.19 (summer) to 1.27 (winter) to convert the E_{pm} to an A-pan equivalent reference potential evaporation, as the water use of natural vegetation, assumed in all runoff-related computations, was based on A-pan equivalent potential evaporation.

Distribution of Annual Reference Potential Evaporation over the Study Area under Historical Climatic Conditions, and Increases under Projected Climate Change

Under historical conditions (1950-1999) annual reference potential evaporation ranges from ~ 1 100 mm in the year in 10 with lowest E_r in the upper Mkomaas to ~ 2 000 mm in the year in 10 with highest E_r in the hot, lower Mooi catchment (**Figure 4.1** left column of maps).

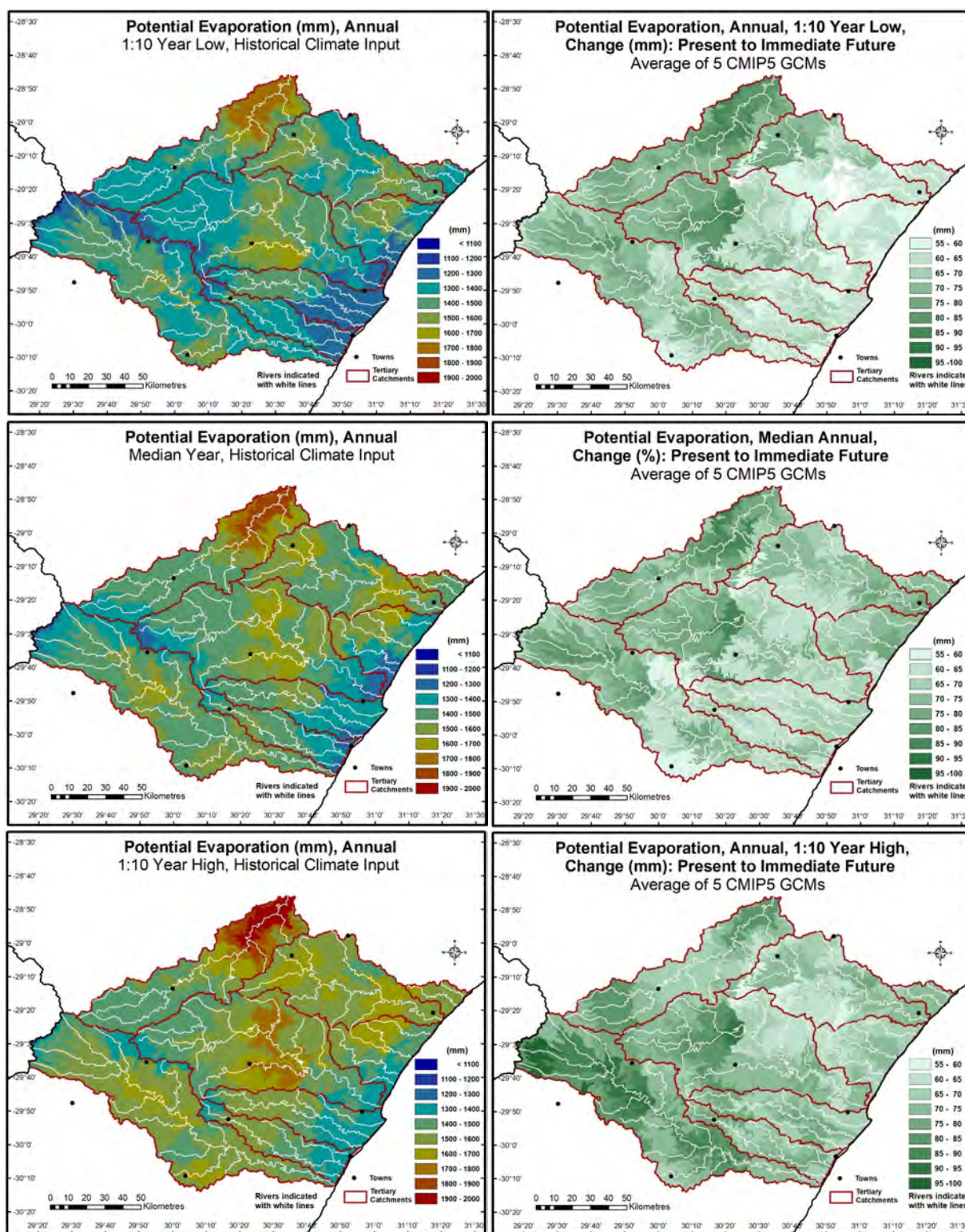


Figure 4.1 Lowest historical annual reference potential evaporation (mm) across the Study Area in 10 years (top left), median annual (middle left) and highest in 10 years (bottom left), and corresponding changes in potential evaporation (mm) from the present to the immediate future, derived from multiple CMIP5 GCMs

Climate projections with CMIP5 GCMs from the present into the immediate future of the 2030s and 2040s show annual increases from as little as 55 mm along the coast, where evaporation is modulated by higher humidity oceanic influences, to ~ 100 mm in the interior where the more sensitive higher changes are considered to be due either to cooler higher altitude

conditions or to already hot and dry conditions (**Figure 4.1** right column of maps). Spatially the changes in E_r due to global warming are relatively consistent in years with low, median or high evaporative demand (**Figure 4.1** right column of maps). When expressed as percentage changes, these range from 2 – 3% along the coast to ~ 10 % in the higher lying west.

Seasonal Reference Potential Evaporation under Historical Climatic Conditions

Seasonal reference potential evaporation under historical conditions is shown in **Figure 4.2**.

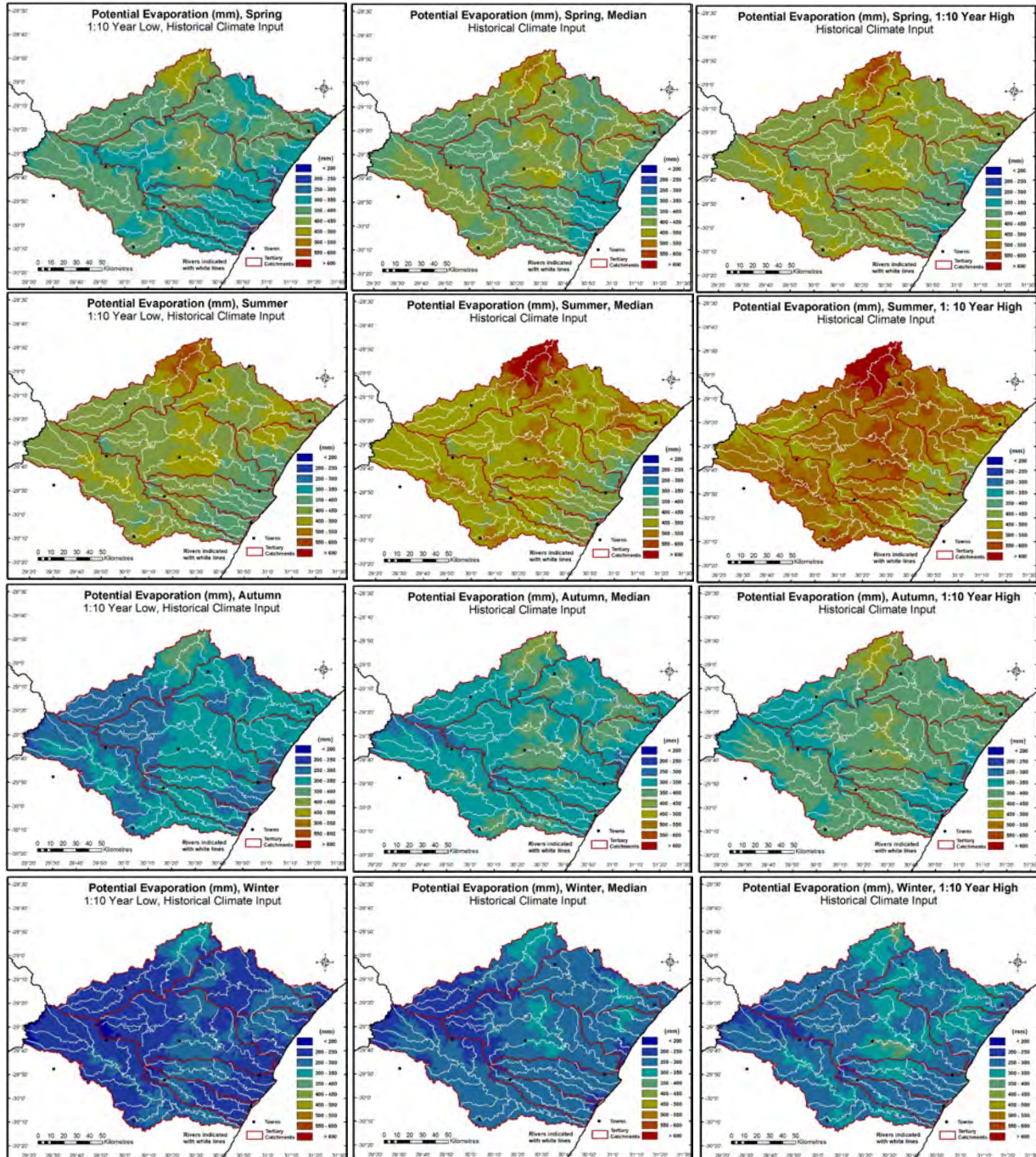


Figure 4.2 Lowest in 10 year (left column), median (middle column) and highest in 10 year (right column) seasonal reference potential evaporation under historical climatic conditions for spring (SON; top row), summer (DJF; 2nd row), autumn (MAM; 3rd row) and winter (JJA; bottom row)

Values in **Figure 4.2** range from < 200 mm in the 3-month winter season from June to August (JJA) to > 600 mm in the summer season from December to February (DJF). As expected, seasonal E_r is highest in summer from ~ 350 to > 600 mm (i.e. ~ 4 to > 6.5 mm/day), followed by spring from September to November (SON) with a range from 300 – 550 mm (~ 3.3 to ~ 6 mm/day), then by autumn from March to May (MAM) during which E_r ranges from 250 – 450 mm (~ 2.8 – 5 mm/day), with least evaporation occurring during the winter season at 200 – 400 mm (i.e. ~ 2.2 to 4.4 mm/day). Thus, even in mid-winter E_r in the Study Area is relatively high. Highest seasonal E_r is, as with annual patterns, in the hot and dry lower Mooi catchment, with lowest values in the high lying west. The increases in seasonal E_r from the 1:10 year low to the 1:10 year high are shown clearly by the red arrow in **Figure 4.2** while, interestingly, under historical climatic conditions the 1:10 summer low spatially matches the 1:10 year spring high and the 1:10 year autumn low matches the 1:10 year winter high.

Projected Increases in Seasonal Potential Evaporation under Climate Change

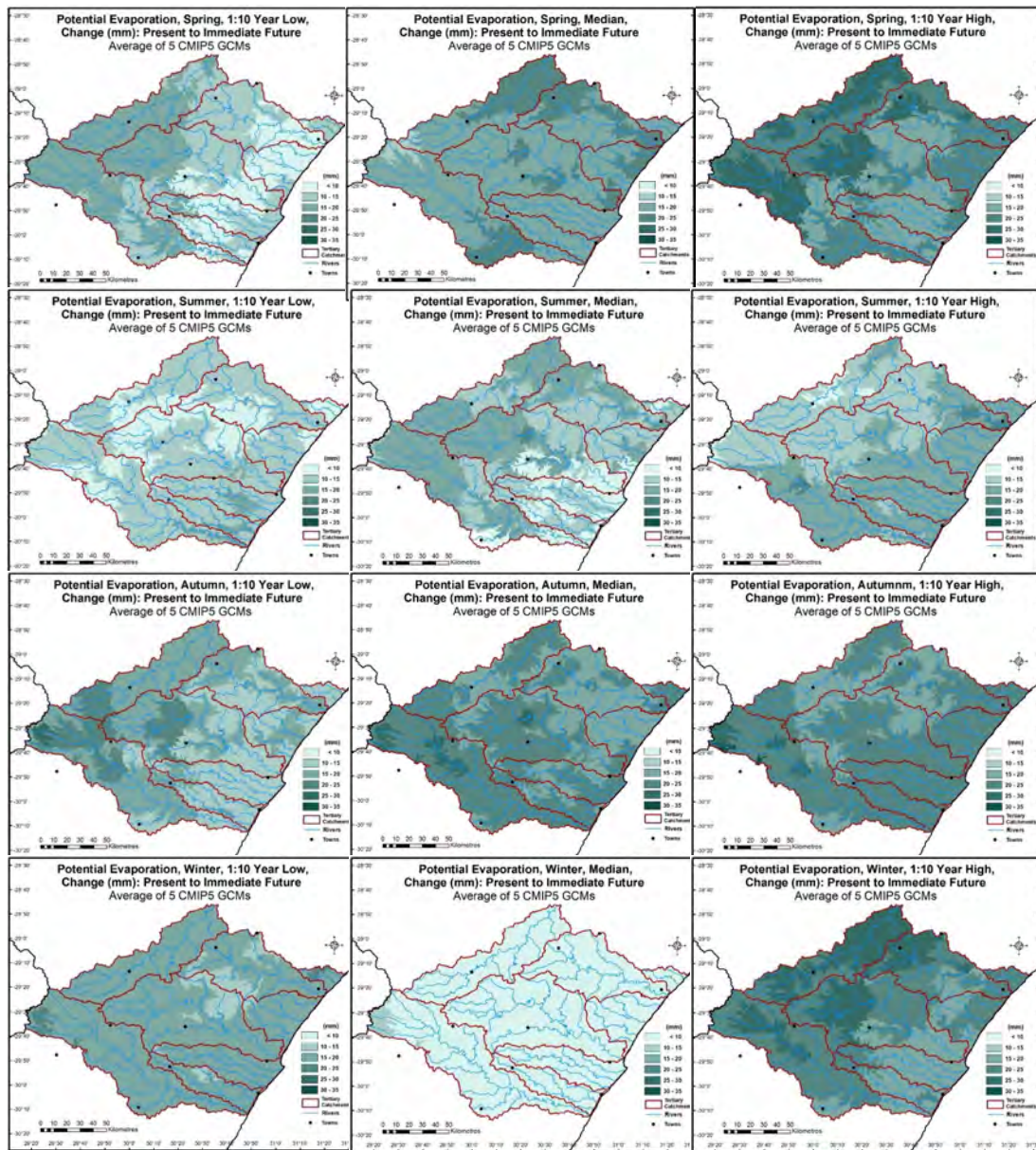


Figure 4.3 Projected increases (mm) from the present to the immediate future in spring (top row), summer (2nd row), autumn (3rd row) and winter (bottom row) reference potential evaporation for a 1:10 year “cool” (left column), a median (middle) and a 1:10 year “hot” year (right), all derived from multiple CMIP5 GCMs

Projected increases in mm from the present to the immediate future in seasonal E_r are shown in **Figure 4.3** for the four seasons, in each case for a 1:10 year “cool” year, a median year and a 1:10 year “hot” year (right). The increases in E_r range from < 10 mm to 35 mm per season, with the highest changes in the transitional seasons of spring and autumn. Spatially, within a specific season, the areas of highest change and, by implication, the most sensitive areas, are not consistent between years of low and of high reference potential evaporation.

Coefficient of Variation of Annual and Seasonal Potential Evaporation under Historical and Projected Climate Change Conditions

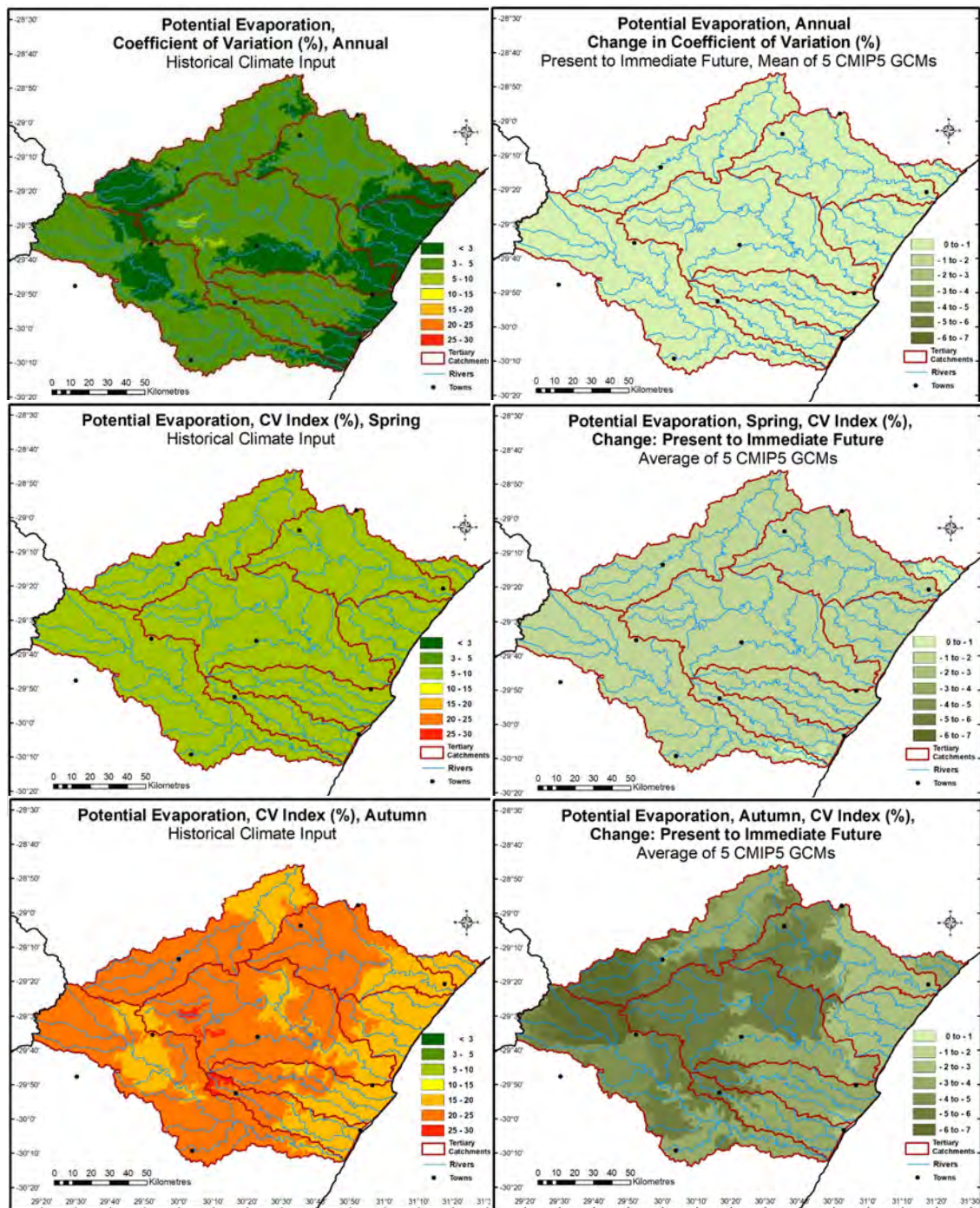


Figure 4.4 Coefficient of variation (%) of inter-annual (top left), inter-spring (middle left) and inter-autumn (bottom left) reference potential evaporation, and their corresponding changes from present to immediate future climates, derived from multiple CMIP5 GCMs

The coefficients of variation (%) of inter-annual, inter-spring and inter-autumn E_r , and their corresponding changes from present to immediate future climates are shown in **Figure 4.4**. The year-to-year variability of annual and seasonal reference potential evaporation is very low when compared with other hydrological variables (see later chapters), at < 5% for annual, < 10% for spring, but up to 25% for autumn CVs. Projected changes in the CV of E_r are also low at < 1% for annual E_r , up to 2% for spring and 5 – 7% in the most inconsistent season, viz. autumn.

Potential Implications for Umgeni Water

Historical annual reference potential evaporation is already high at around 1 500 mm and up to 2 000 mm, and with climate projections into the immediate future of the 2030s and 2040s annual increases between 60 and 100 mm, which are equivalent to 2 – 3% along the coast to ~ 10 % in the higher lying west, may be expected. Seasonal E_r ranges from 200 mm in winter up to 600 mm in summer. Potential evaporation from dams, wetlands and riparian zones thus constitutes an unavoidable loss to Umgeni Water – a loss which will be exacerbated into the future. Additionally, all else remaining the same, soils are anticipated to dry out more rapidly in future, with this having potential negative implications on runoff production. Furthermore, irrigation water demands in the immediate future will be higher than at present, affecting Umgeni Water both by abstractions from dams being increased and by river flows being reduced where irrigation is from run-of-river.

CHAPTER 5 RAINFALL

Setting the Scene

Among the various individual climatic variables which influence the generation of runoff in the Study Area, as in most of South Africa, the most important one is considered to be rainfall. The focus of water resource managers is invariably on the patterns of rainfall in time and over an area, by asking

- how much it rains in the long term,
- where it rains (its spatial distribution),
- when it rains (its seasonal distribution),
- how variable the rainfall is from year to year, or for a given season, and
- what the duration and frequency of dry and of wet spells are.

These questions are addressed for the Study Area in this chapter (and in other chapters) from perspectives of both historical climatic conditions and of projected climate changes in rainfall characteristics.

Annual Rainfall under Historical Climatic Conditions

Annual precipitation characterises the long-term quantity of water available to a region for hydrological (and agricultural) purposes, and it provides an upper limit to a region's sustainable water resources. Mean annual precipitation, MAP, is often used as the key indicator of the rainfall of a region, but the concept of MAP nevertheless has its weaknesses, in that years with low rainfall are generally more numerous than the higher than average years, and with MAPs frequently inflated by a few very high annual totals from very wet years. Hence the concepts of median annual rainfall, being the mid-value of a time series of annual rainfalls, as well as rainfall in a defined dry year and a defined wet year such as those occurring statistically once in 10 years, are more useful indicators of the hydrological potential of a region.

Under historical climate (1950 – 1999) median annual rainfall across the Study Area ranges from ~ 600 to ~ 1 200 mm, with this range decreasing to < 500 to ~ 800 mm in the statistically 1:10 dry year and increasing to ~ 700 to > 1 300 mm in the 1:10 wet year (**Figures 5.1** and **5.2**). Annual rainfalls are highest along the coast and in the far inland at high altitudes.

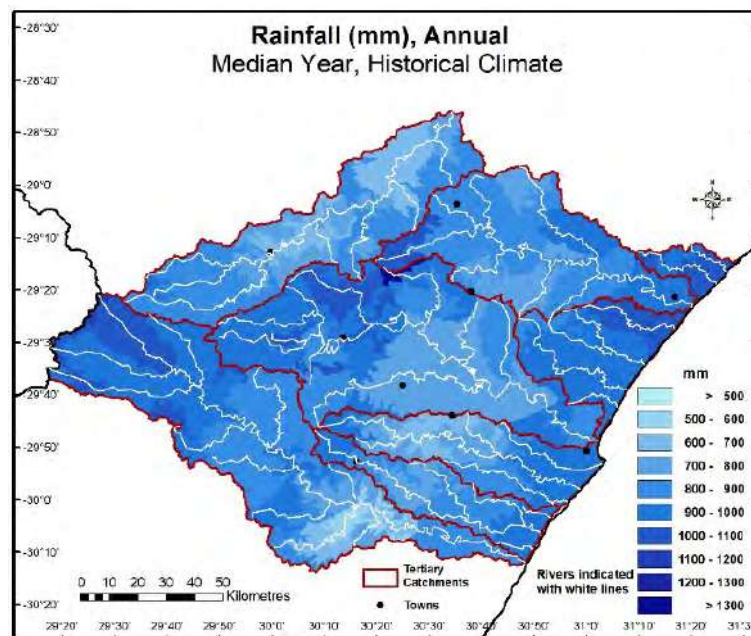


Figure 5.1 Median annual rainfall (mm) in the Study Area

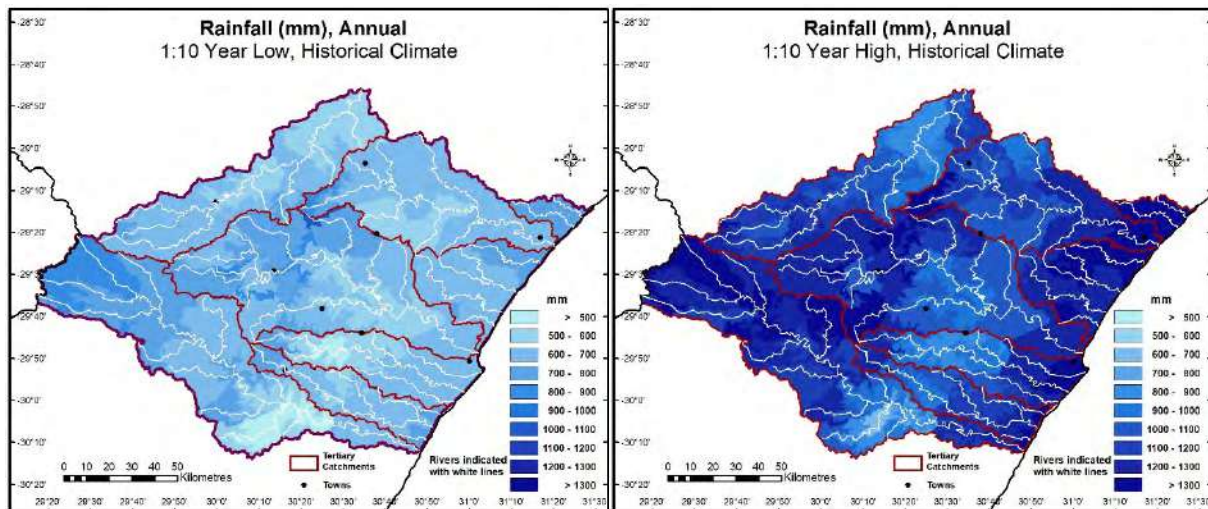


Figure 5.2 The lowest annual rainfall in 10 years (left) and the highest annual rainfall in 10 years (right), all under historical climatic conditions (1950-1999)

Projected Changes in Annual Rainfall under Conditions of Climate Change

Using outputs from multiple CMIP5 GCMs, the averaged projected changes from the present to the immediate future for the lowest annual rainfall in 10 years, for a year of median rainfall and for the highest annual rainfall in 10 years are shown in **Figure 5.3**, with changes expressed as absolute changes in mm, as relative changes in % and as a ratio change as each of these three expressions of change have individual meaning.

Umgeni Water's area of interest is shown in **Figure 5.3** to be one of both "winners and losers" according to the CORDEX GCMs used in this Study. In dry years projections are for a slight drying by 10 – 20 mm, equivalent to < 2% along the southwest and northwest boundary areas and in patches along the coast, offset by projected increases by ~ 2% in the norther half of the Study Area. In years of median annual rainfall the drying in the west is more pronounced at > 50 mm in places, equivalent to a 2 – 5% reduction. In wet years the prognosis is largely positive over large tracts of the interior, with increases of ~ 50 mm, or 2 – 5%, and with the projected decreases much patchier along the higher lying west and parts of the coast.

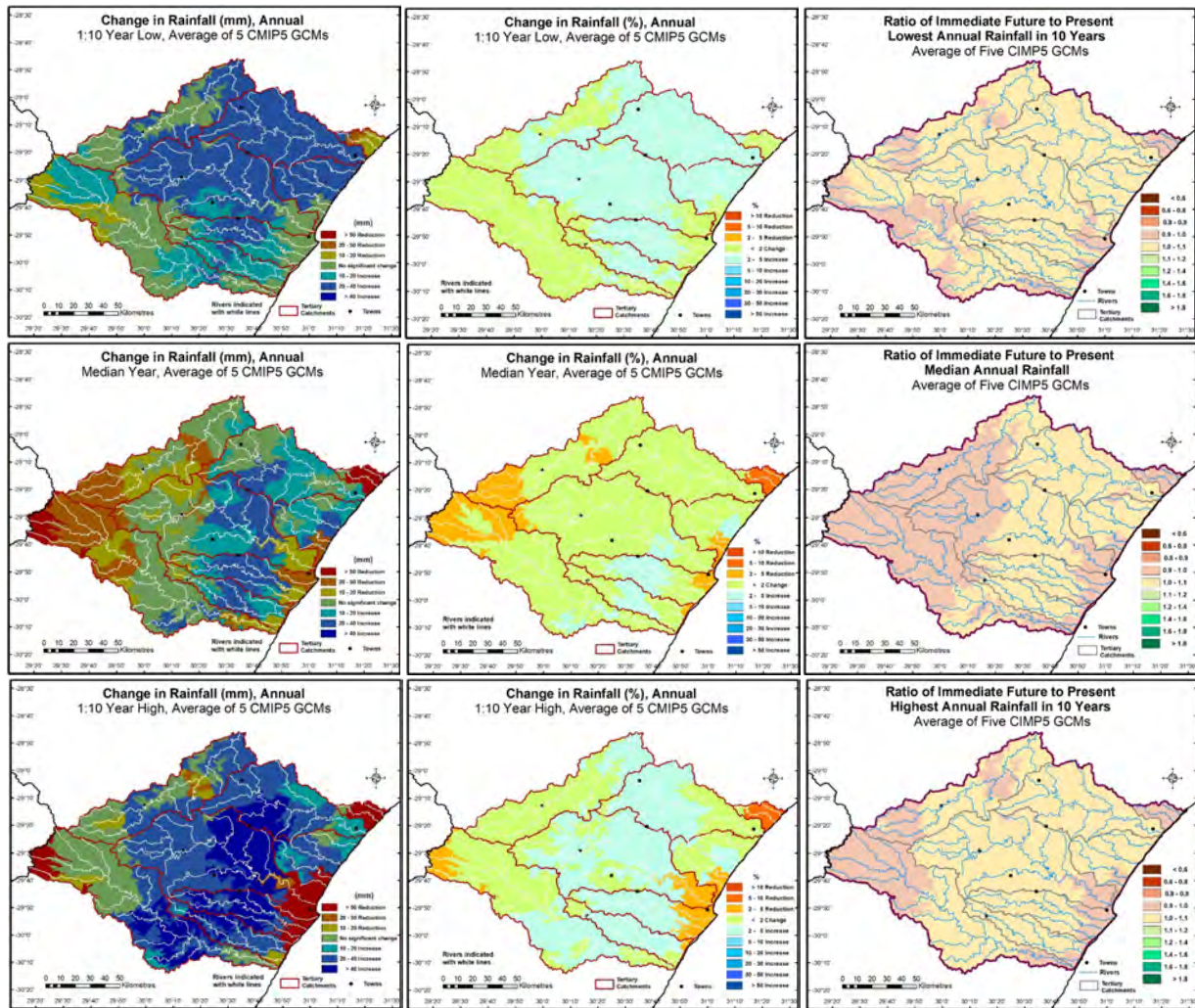


Figure 5.3 Projected changes from the present to the immediate future in the lowest annual rainfall in 10 years (top maps), in a year of median rainfall (middle) and in the highest annual rainfall in 10 years (bottom maps), expressed as absolute changes in mm (left column of maps), as relative changes in % (middle column of maps) and as a ratio (right column of maps), all derived as means of changes from multiple CMIP5 GCMs

Seasonal Rainfall: Setting the Scene

While it is important in water resources (and agriculture) planning and operations to have knowledge on *whether*, in which *direction* and by *how much* annual rainfall is projected to change into the future, it is arguably equally if not more important to ask the same questions about seasonal rainfall. This is so because there are seasons of high flows and of low flows, because the antecedent soil moisture conditions from one season may affect runoff generation of the succeeding season and because baseflows in one season are frequently the “residual” of excessive rainfall of the season preceding it.

Analyses with historical data as a baseline, and with the CMIP5 CORDEX suite of GCMs for projected changes, were therefore undertaken, and confidence levels in the results assessed, of

- spring rainfall, assumed to be September, October and November (SON),
- summer rainfall, assumed to be December through February (DJF),
- autumn, i.e. March to May (MAM), and
- winter rainfall, i.e. June to August (JJA).

Seasonal Rainfall under Historical Climatic Conditions

Maps of spring (SON), summer (DJF), autumn (MAM) and winter (JJA) rainfall under driest year in 10 conditions, median year and wettest year in 10 conditions are shown in **Figure 5.4** for historical climatic conditions (1950 – 1999), with seasonal totals ranging from < 10 mm in places in dry winters to > 700 mm in places in wet summers.

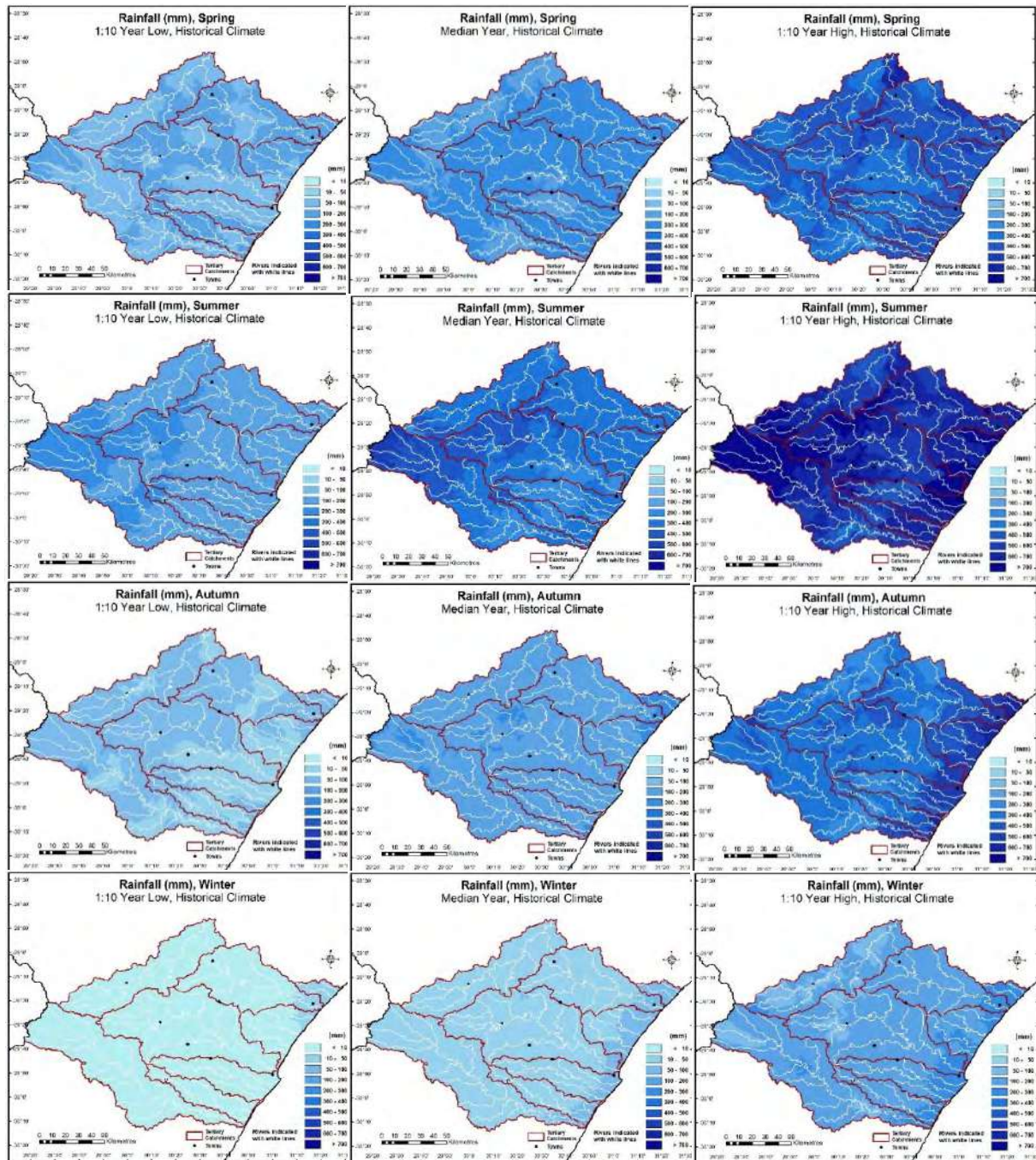


Figure 5.4 Historical spring (top row of maps), summer (2nd row), autumn (3rd row) and winter (bottom row) rainfall under driest year in 10 conditions (left column of maps), median year (middle column) and wettest year in 10 conditions (right column of maps)

Projected Changes in Seasonal Rainfall under Conditions of Climate Change

Spring (September to November)

Projections into the future from multiple CORDEX CMIP5 global climate models indicate an overall increase in spring rainfall into the immediate future of the 2030s, with ratios of change generally in the positive (1.0 – 1.1) except for a few patches (**Figure 5.5** top row), and when expressed in mm changes, with essentially no changes in dry years but with increases of 10 – 20 mm and even more over the majority of the Study Area in median and wet years (middle row of maps), which equates to increases of between 2 and 10% (**Figure 5.5** bottom row). The prognosis is thus essentially positive.

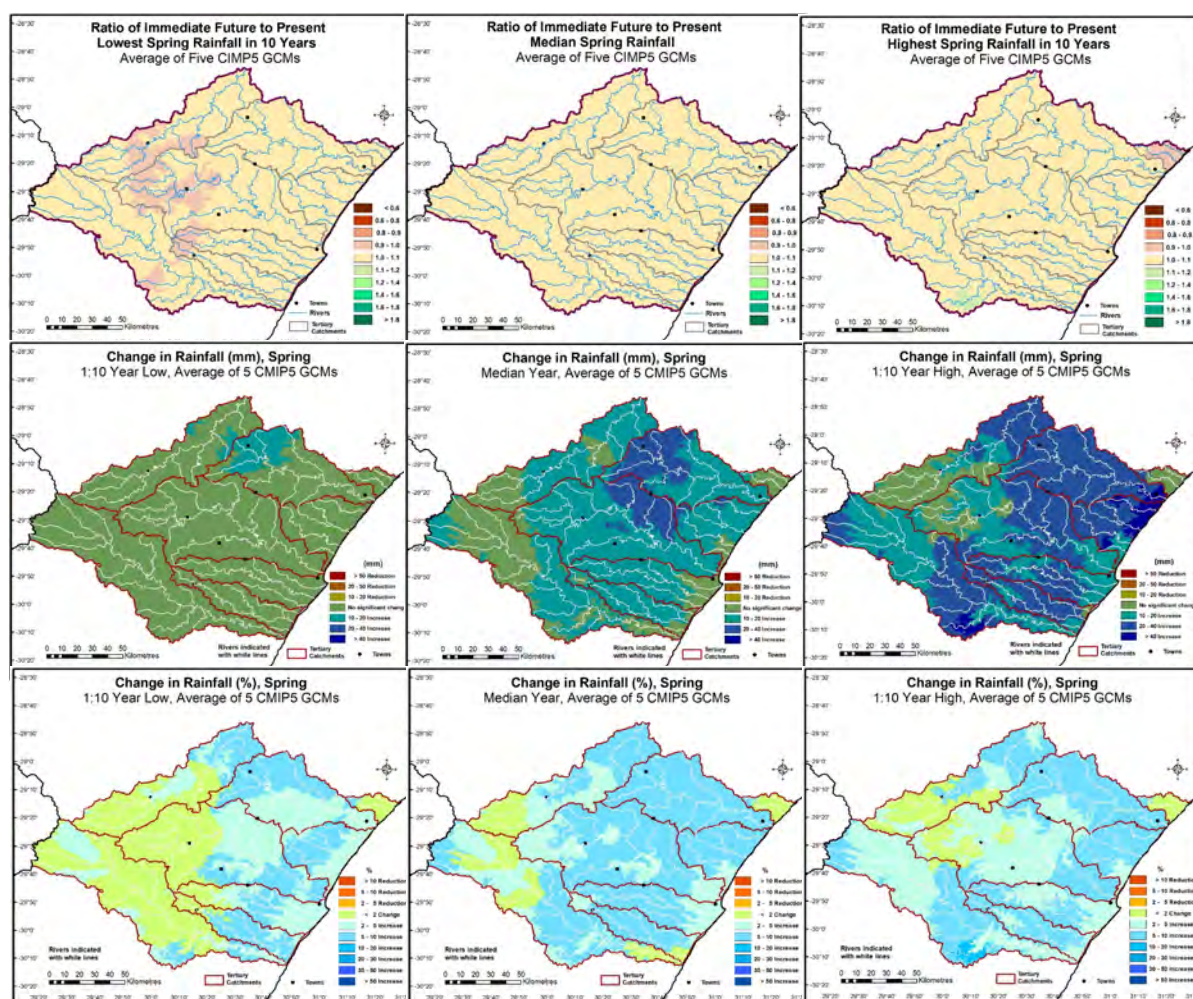


Figure 5.5 Projected changes in spring rainfall from the present to the immediate future, as a ratio (top row), in mm (middle row) and as a percentage change (bottom row), for the driest year in 10 (left column), the median year (middle) and the wettest year in 10 (right column), all derived from outputs of multiple GCMs

Summer (December to February)

Projections into the future from multiple CORDEX CMIP5 global climate models indicate more complex spatial patterns than those of spring. Some increases in summer rainfall are projected into the immediate future of the 2030s, with ratio changes largely in the range 1.0 – 1.1 except for patches along the coast and the southern boundary where they drop to below 1.0 (**Figure 5.6** top row). Ratios by themselves are, however, deceptive as the summer months receive the bulk of the year's rainfall, and absolute increases of 10 – 40 mm are displayed over much of the interior, with simultaneously decreases of 20 mm and even up to 50 mm in the critical upland catchment areas of the extreme west as well as along parts of the coast (**Figure 5.6** middle row), with these projected changes translating into 5 – 10% increases and, importantly,

up to 50% in wet years in the south with, however, simultaneously displaying decreases of 10% and more in parts (**Figure 5.6** bottom row).

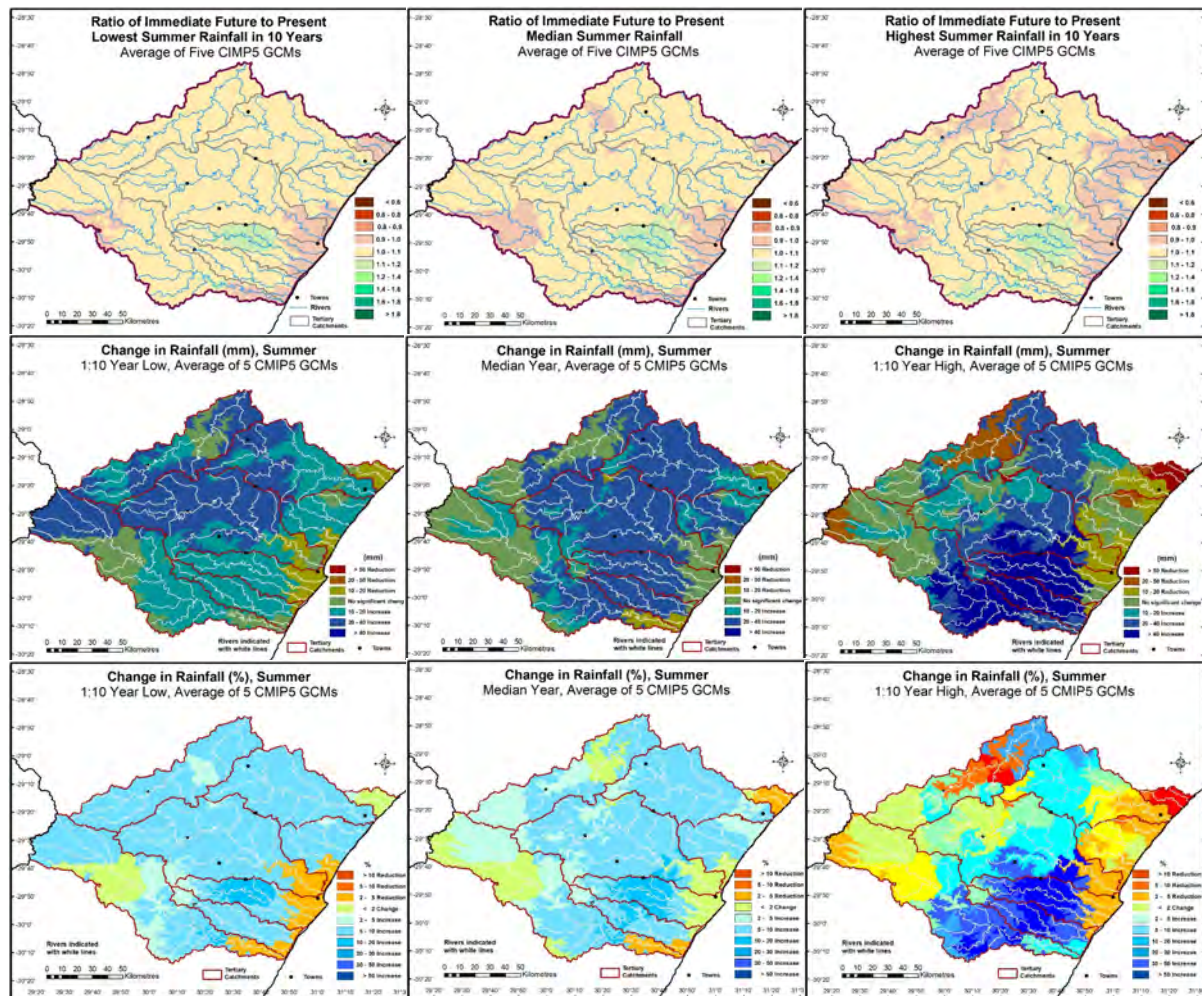


Figure 5.6 Projected changes in summer rainfall from the present to the immediate future, as a ratio (top row), in mm (middle row) and as a percentage change (bottom row), for the driest year in 10 (left column), the median year (middle) and the wettest year in 10 (right column), all derived from outputs of multiple GCMs

Autumn (March to May)

Projected autumn changes in autumn rainfall differ markedly from those of spring and summer in that ratio changes show large areas with both values above and below unity (1), but these translating into decreases of 30 mm and up to 50 mm in median years in the critical western catchments which are largely the sources areas of runoff, while in wet years the northern parts of the Study Area are projected to experience largely significant increases in rainfall (**Figure 5.7** top and middle rows). Expressed as percentage changes, median years are projected to experience decreases in autumn rainfall of 5 – 10% and more in the west and increases of 5 – 10% and more in the northern parts (**Figure 5.7** bottom row).

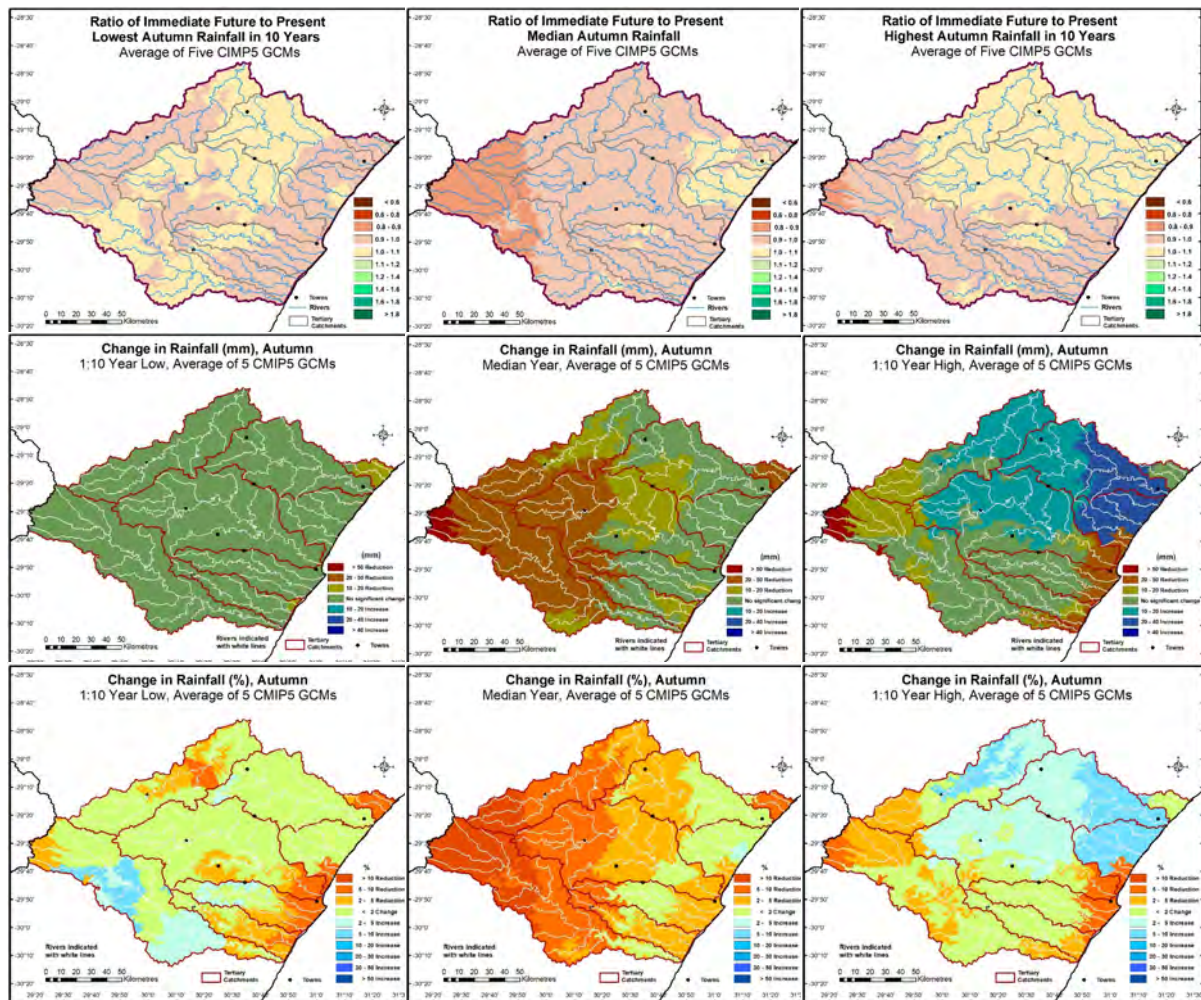


Figure 5.7 Projected changes in autumn rainfall from the present to the immediate future, as a ratio (top row), in mm (middle row) and as a percentage change (bottom row), for the driest year in 10 (left column), the median year (middle) and the wettest year in 10 (right column), all derived from outputs of multiple GCMs

Winter (June to August)

Some of the winter rainfall changes projected into the immediate future in **Figure 5.8** may look relatively extreme to the eye, but, as such, changes in winter rainfall are of relatively little significance in the Study Area because winter constitutes the dry season. Thus, when the very low rainfalls in dry years show ratio increases of 1.2 to 1.8 and high percentage increases, these translate to no significant change in mm terms (**Figure 5.8** left column of maps). In median and wet years projected changes display mixed spatial patterns, but again in real terms these changes will have minimal hydrological impact.

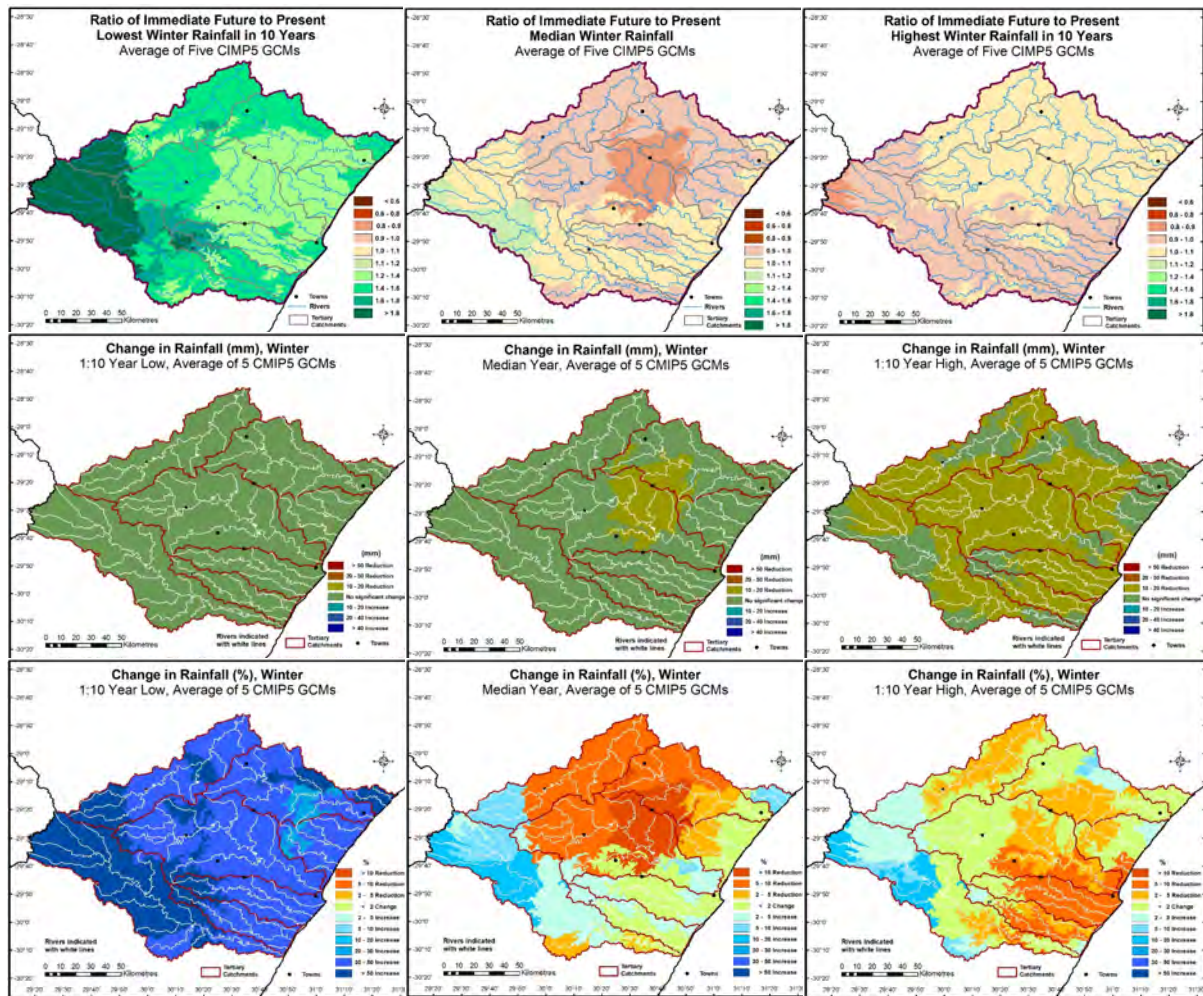


Figure 5.8 Projected changes in winter rainfall from the present to the immediate future, as a ratio (top row), in mm (middle row) and as a percentage change (bottom row), for the driest year in 10 (left column), the median year (middle) and the wettest year in 10 (right column), all derived from outputs of multiple GCMs

Coefficient of Variation of Annual and Seasonal Rainfall under Historical and Projected Climate Change Conditions

Year-to-year coefficients of variation, CV%, of annual and seasonal rainfall and their projected changes are shown in **Figure 5.9**. The CV% of annual rainfall is, by South African levels, very low at < 40%, and into the future is projected not to change much, with reductions up to 2% along the coastal zones and increases by 1 – 2% in the interior (**Figure 5.9** top left and right).

Seasonally a very different pattern emerges when historical rainfall variability is assessed, with spring CV% of rainfall between 100 and 300%, summer around 200%, autumn between 100 and 300% and winter season CV% generally in excess of 300% (**Figure 5.9** left column of maps). Seasonal changes in rainfall CV% into the immediate future display both increases and decreases (**Figure 5.9** right column of maps), with reductions of 2 – 3% along the coast in spring, the northern border of the Study Area in summer, the south in autumn and parts of the coast and the northwest border area in winter. Simultaneously, however, the CV% of spring rainfall is projected to increase in the central-west by up to 3% (albeit from a baseline CV% of 200 – 300%, in the southern half in summer (again from a baseline of 200 – 300%), by up to 6% in autumn and by 2 – 6% in winter (but from a baseline > 300%).

The conclusion is, therefore, that changes in the CV% of rainfall will be insignificant.

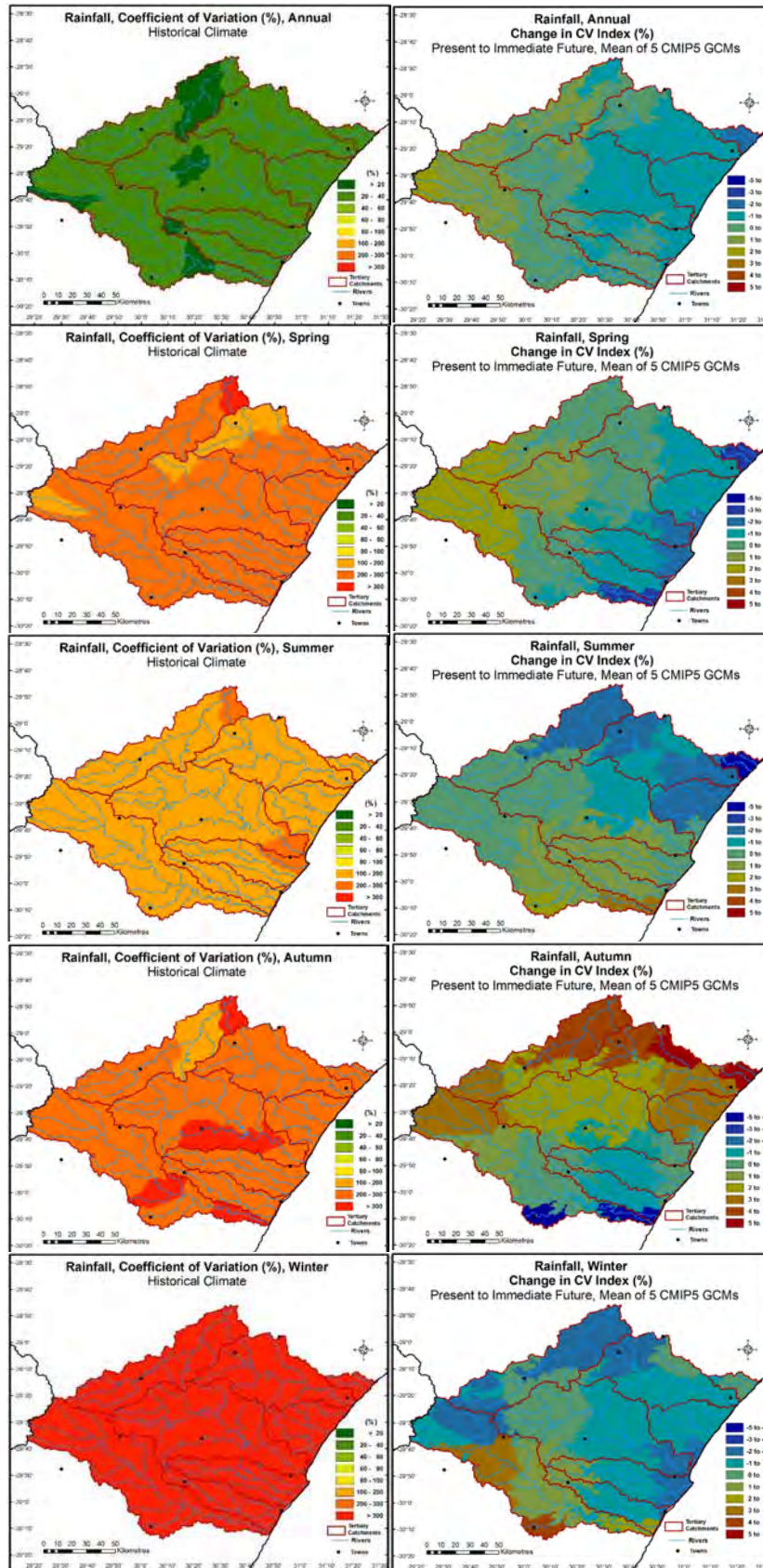


Figure 5.9 Inter-annual coefficient of variation (CV%) of rainfall (top left), as well as the CV% of spring (2nd left), summer (3rd left), autumn (4th left) and winter rainfall (bottom left), all under historical climatic conditions, with corresponding projected changes in annual and seasonal CVs from present to immediate future climatic conditions, derived from outputs of multiple CMIP5 GCMs

Confidence in Results: Background

In the process representations of GCMs assumptions are made into future, for example, on Greenhouse Gas Emissions, population growth and land uses. Additionally, the internal dynamics of individual GCMs are different. For a given Representative Concentration Pathway, therefore, individual GCMs will give different answers, not only of more primary outputs such as temperature, but even more so of derived/secondary outputs such as rainfall. For ideal prognoses of climate variables into the future, a series of GCMs would all give identical answers, or at minimum answers close to one another. This is not the case, however, and for that reason already outputs from multiple GCMs are used and an average of the answers is mapped, as in this Report.

If all GCMs gave identical/near-identical answers, confidence in prognoses into the future would be high. Because they do not, however, uncertainties in results exist, and confidence assessments have to be undertaken. Confidence assessments can be undertaken by a wide range of statistical procedures. One of the simplest is to take the range of answers from multiple GCMs and to compute the Coefficient of Variation (%) of the answers. If the CV% is low, the GCMs are giving similar answers/outputs and confidence in results is considered to be high, and if the CV% is high because GCM outputs vary widely, confidence in the results is considered low.

This approach has been adopted in this Study, with the CV% termed the “Confidence Index”, or CI. By way of example, a CI below 10 is considered to be a result of “very high” confidence (i.e. with only very low uncertainty), 10 – 20 is “high”, 20 – 40 is considered “acceptable”, 40 – 60 is a result with “low” confidence and CI > 60 displays “very low” confidence (i.e. there exists very high uncertainty). The example in **Figure 5.10** illustrates the entire range of confidences in the results shown.

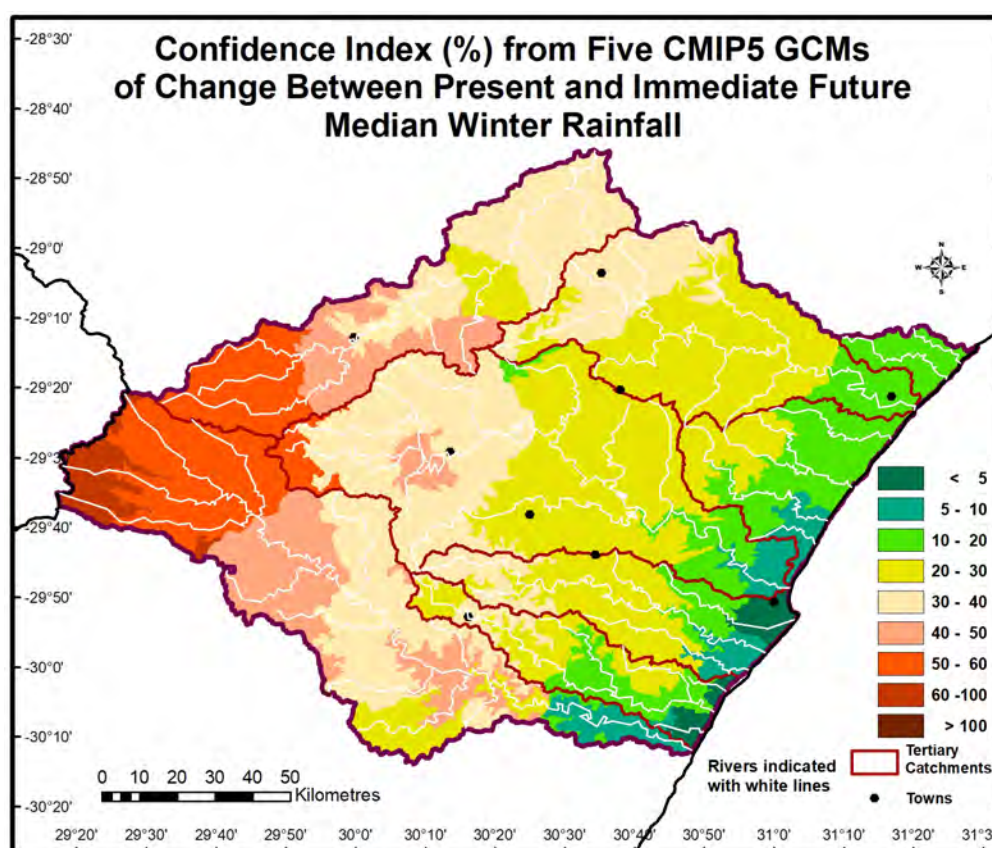


Figure 5.10 Example of a mapped confidence in results with a range in confidences from very high (CI < 10; dark green) to very low (CI > 60; dark red)

Confidence in Seasonal Changes of Rainfall from the Present into the immediate Future

Seasonal confidence indices of changes between present and immediate future rainfalls in the Study Area are shown in **Figure 5.11** for spring (top row of maps), summer (2nd row), autumn (3rd row) and winter (bottom row) for the lowest flows in 10 years (left column of maps), median flows (middle column) and the highest flows in 10 years (right column). Two observations stand out, viz. that for a given season confidence in results is lowest in dry years and highest in wet years and, secondly, that confidence in results depends on the season, being lowest in winter, second lowest in autumn and highest in spring.

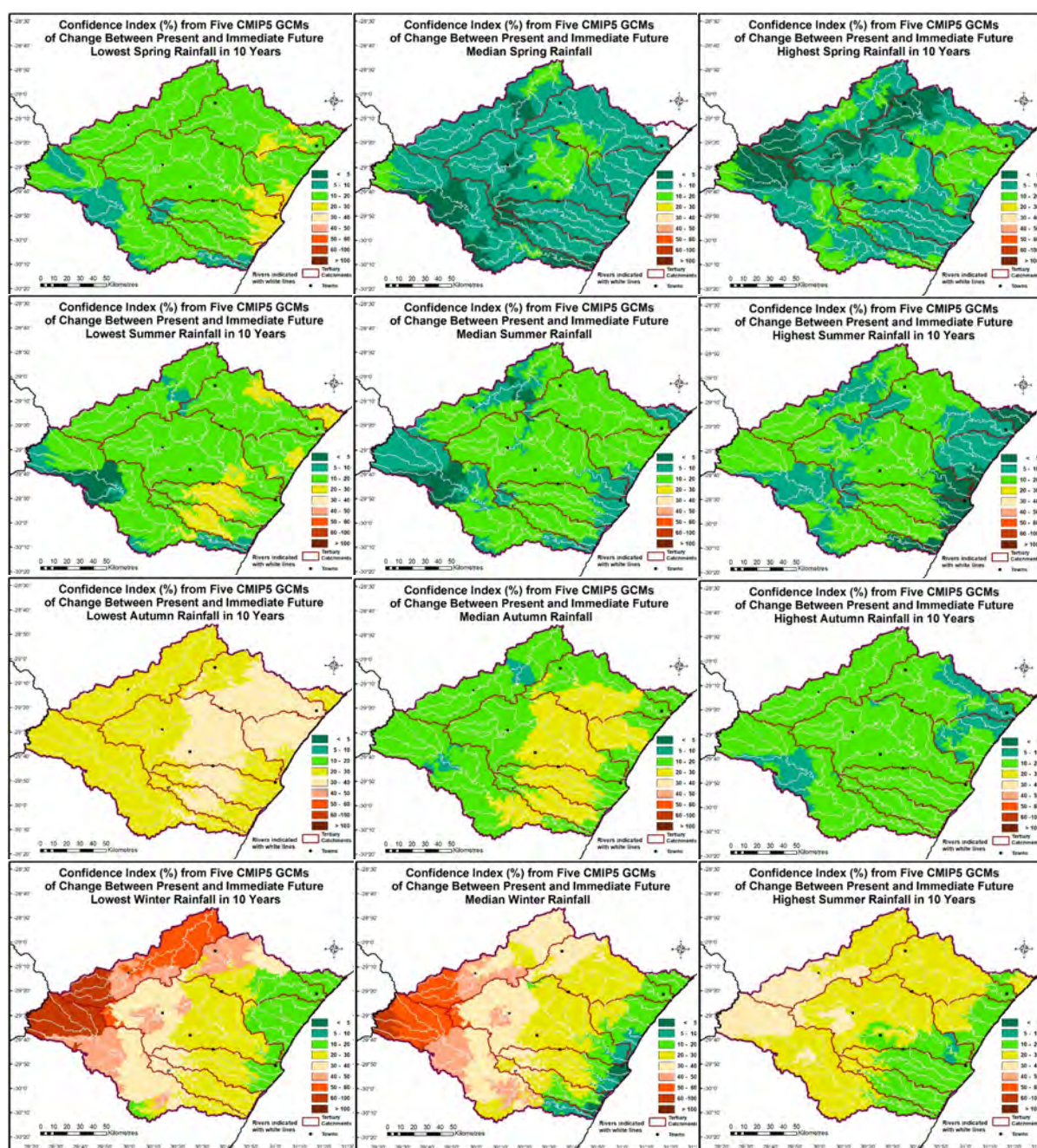


Figure 5.11 Seasonal confidence indices of changes between present and immediate future rainfalls in the Study Area for spring (top row of maps), summer (2nd row), autumn (3rd row) and winter (bottom row) for the lowest flows in 10 years (left column of maps), median flows (middle column) and the highest flows in 10 years (right column)

CHAPTER 6 DRY SPELLS

Setting the Scene

Dry spells may be described as a creeping, slow on-setting natural hazard, which can manifest itself either through a lack of precipitation, or from a lack of available soil moisture for crops, or a reduction of streamflows below a critical threshold, or of the amount of water stored in reservoirs, or reduced levels of groundwater (Schulze, 2003; Schmidt-Thomé, 2006). However, unlike aridity, which is a permanent feature of the climate in low rainfall areas, dry spells are a temporary aberration that can occur in low as well as high rainfall areas.

Dry spells have both direct and indirect consequences for human livelihoods. A direct consequence of a dry spell is a crop loss which can, in turn, result in starvation among humans if alternative food sources are not available. Indirectly, a dry spell expressed through a water shortage may contribute to the proliferation of diseases when people lack water for basic hygiene (Schulze, 2003). Owing to the projected increases in temperature and changes in rainfall amounts and variability in future climates, it is anticipated that the frequency as well as the duration and magnitude of dry spells will change, either increasing or decreasing, with potentially severe economic, social and environmental implications. It is therefore necessary to try and assess how these hazards might change in future climates

What Do We Understand by Dry and Wet Spells?

There are many definitions of dry spells and of wet spells within a context of water resource management. For this Report, three durations of dry spells were considered for each Quinary catchment covering the Study Area, viz. periods of either 2 consecutive months, or of 3 or of 6 consecutive months of below normal rainfall. Normal rainfall for a 2, or 3, or 6 month period is defined as the sum of the median monthly rainfalls from a long rainfall record for the duration under consideration and for the Quinary being assessed.

While not identical to, this approach of using median values of rainfall for consecutive months as the criterion for identifying dry spells is in line with approaches taken by others, e.g. UNDP (2004) or Lehner *et al.* (2006).

How Were Dry Spells Determined and Mapped?

Since each Quinary has a unique median rainfall for each month of the year, the criteria for identifying a dry spell is unique to that Quinary. For a dry spell of a defined duration (i.e. 2 or 3 or 6 consecutive months) to be identified as “dry” when analysing a monthly sequence of rainfalls over a 30 or 50 year period, its rainfall has to be 10% or more below the median. The number of dry spells of a defined duration (e.g. 3 consecutive months) in the years being assessed (e.g. a 30 year record from GCMs) are summed and then divided by the number of years in order to obtain a probability of dry spells per year, which is then mapped.

Note that in this evaluation neither the severity nor the seasonality of the dry spells are considered, only the frequency per annum. In this Study 2 consecutive months constitutes a mild dry spell, 3 a moderate and 6 consecutive below normal months a severe dry spell.

In order to assess the impact of projected climate change on dry spells across the Study Area, dry spell frequencies first computed for a given duration using the 50 year historical record in order to obtain a “reference”, or baseline. Thereafter dry spell frequencies were computed from multiple CORDEX, i.e. CMIP5, GCMs for “present” climatic conditions for the 30 year period from 1976-2005, and then for the immediate future from 2016-2045. Changes in the frequencies of dry spells, be they higher (implying more dry spells in future) or lower (signifying fewer dry spells in future), could then be computed on a Quinary basis, and mapped.

Dry Spells under Historical Climatic Conditions and Projected Changes in Dry Spells from the Present into the Immediate Future

Average numbers of 2 consecutive month dry spells per annum, 3 consecutive month and 6 consecutive month dry spells per annum are shown in **Figure 6.1** for historical climatic conditions, along with corresponding changes in occurrences per annum from the present into the intermediate future, the latter derived from outputs of multiple CMIP5 GCMs.

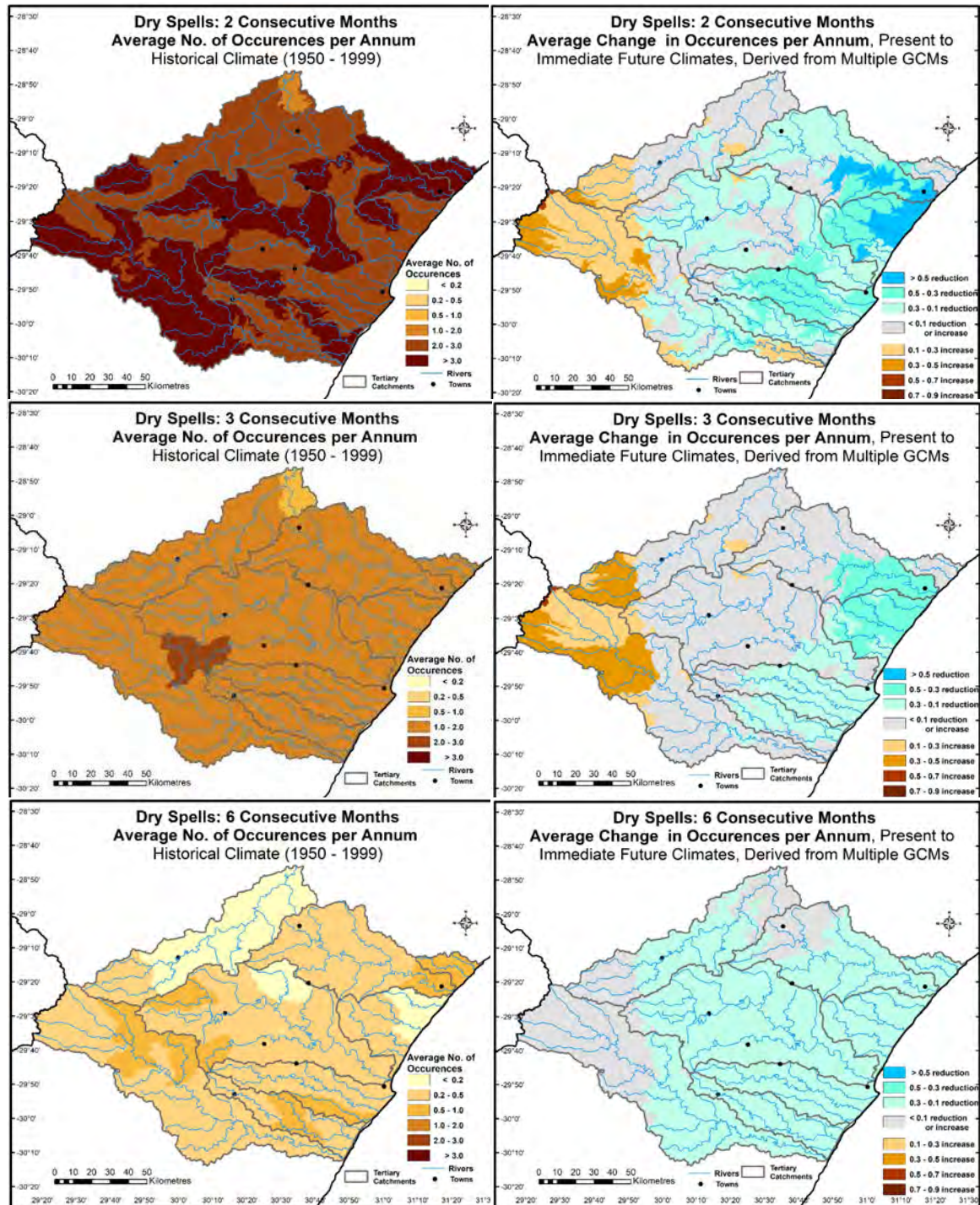


Figure 6.1 Average number of two consecutive month dry spells per annum (top left), three consecutive month (middle left) and six consecutive month dry spells per annum (bottom left) under historical climatic conditions and corresponding changes in occurrences per annum from the present into the intermediate future (right column), the latter derived from outputs of multiple CMIP5 GCMs

Under historical climatic conditions **Figure 6.1** shows that on average 2 to 3 dry spells of 2 consecutive months occur per year across the Study Area, this reducing to 1 to 2 dry spells of 3 consecutive months and to between 0.2 and 0.5 six month dry spells with, in places up to one 6 month dry spell per year.

From the present of 1976 to 2005 into the immediate future of 2016 to 2045 the CMIP5 GCMs used in this Study are projecting areas of both increases and reductions in dry spells for the 2 and 3 consecutive month durations, with reductions in the west and increases along the coast, while for 6 consecutive months the number of dry spells per annum is projected to be reduced over most of the Study Area.

Potential Implications for Umgeni Water

Dry spells of short and medium duration are a concern to water resource managers as they imply increases in irrigation water requirements and reductions in runoff. The projections of more dry spells per annum of 2 and 3 consecutive months' duration over the next 30 years would constitute a further concern to Umgeni Water as they are shown, according to the GCMs used, to occur in the higher lying western source areas of major rivers in the Study Area.

CHAPTER 7 WET SPELLS

Defining and Computing Wet Spells of Varying Durations across the Study Area

Wet spells in this analysis are the inverse of dry spells, with again three durations having been considered for each Quinary Catchment covering the Study Area, in this instance periods of either 2 consecutive months, or of 3 or of 6 consecutive months of **above** normal rainfall. Again, “normal” rainfall for a 2 or 3 or 6 month period was defined as the sum of the median monthly rainfalls from a long rainfall record for the duration under consideration and for the Quinary being assessed. Once more, for a wet spell of a defined duration (i.e. 2 or 3 or 6 consecutive months) to be identified as “wet” when analysing a monthly sequence of rainfalls over a 30 or 50 year period of time, its rainfall had to be 10% or more *above* the median. The number of wet spells of a defined duration (e.g. 3 consecutive months) in the years being assessed (e.g. a 30 year record) were summed and then divided by the number of years in order to obtain probabilities of wet spells per year, which were then mapped.

Findings on Distributions of Wet Spells of Varying Durations across the Study Area and Projected Changes with Global Warming

In the left hand column of **Figure 7.1** the average number of 2 consecutive month wet spells per annum, 3 consecutive month and 6 consecutive month wet spells per annum are shown for historical climatic conditions, with the right hand column displaying corresponding changes in occurrences per annum from the present into the immediate future, these having been derived from outputs of multiple CMIP5 GCMs.

Under historical climatic conditions an average of 2 to more than 3 wet spells per annum of 2 consecutive months are experienced across the Study Area, this reducing to 0.5 to 1 wet spell of 3 months’ and to between 0.2 and 0.5 wet spells of 6 consecutive months’ duration.

The climate change analysis shows wet spells of 2 and 3 consecutive months’ duration to reduce significantly in the west while increasing across the eastern two-thirds of the Study Area. Projected changes for the 6 consecutive month duration wet spells are much more muted, but with still slight reductions in the extreme west and increases across most of the east.

Potential Implications for Umgeni Water

The projected decline in wet spells, especially those of 2 and 3 months’ duration, in the west imply fewer runoff producing events per year in that critical source area of runoff as well as increases in irrigation water requirements there. These findings might be offset by projected increases in wet spells in the eastern two-thirds of the Study Area.

Arguably the biggest concern to Umgeni Water is the “double whammy” in the west of the Study Area, where both increases in dry spells and simultaneously decreases in wet spells per annum are projected by the CORDEX GCMs utilised in this Study, especially since the west is a critical source area of runoff within the region.

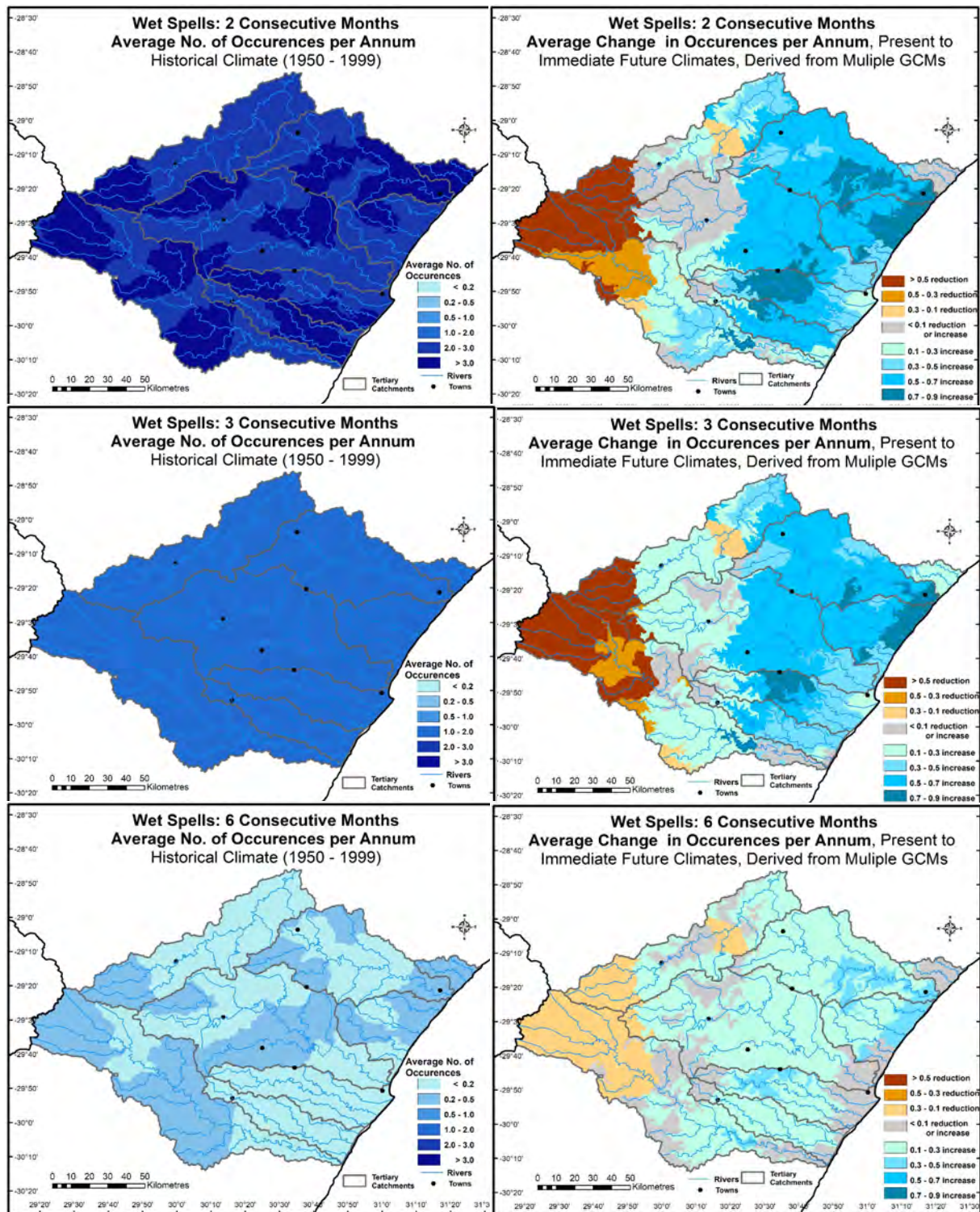


Figure 7.1 Average number of two consecutive month wet spells per annum (top left), three consecutive month (middle left) and six consecutive month wet spells per annum (bottom left) under historical climatic conditions and corresponding changes in occurrences per annum from the present into the intermediate future (right column), the latter derived from outputs of multiple CMIP5 GCMs

CHAPTER 8 ACCUMULATED STREAMFLOW

Clarifying Some Runoff Related Terminology Used

When the theme of water is under discussion, terms such as catchment, runoff, stormflow, baseflow and streamflow are often used. These terms are clarified below in the context that they are used in this Report.

Catchment

A catchment is a topographically defined basin, or watershed area, which collects water and drains it at an exit. In this Report, the term also frequently refers to a fifth level so-called Quinary Catchment as defined and delineated by the Centre for Water Resources Research at the University of KwaZulu-Natal (Schulze and Horan, 2010). The RSA, Lesotho and Swaziland have been delineated into 5 838 Quinary Catchments, and with water cascading downstream from one Quinary to the next until it reaches the ocean or exits into a neighbouring country, these Quinaries are hydrologically interlinked. In results that follow in this specific Chapter (but not in many of the others) the runoff responses from individual Quinaries are accumulated downstream, i.e. the streamflow generated within a Quinary Catchment is added to that of downstream catchments, and any runoff from upstream catchments is taken into account when a given catchment's streamflow is calculated.

Runoff

Runoff, in the context of this Report, is water generated from a topographically defined catchment and which flows in defined channels. It consists of stormflows plus baseflows. In this Report the term "streamflow" is *not* used synonymously with runoff (see definition below). In an operational catchment, runoff includes any seepage, environmental flow releases and overflows from any dams in a catchment, if they are present - which is not the case in any of the simulations in this Report in which baseline (natural vegetation) catchment conditions are assumed.

Stormflow

Stormflow is the component of runoff generated at or near the surface within the catchment from a specific rainfall event. Part of that stormflow has a rapid (or quickflow) response, which is the runoff occurring on the same day as the rainfall, with the remainder being delayed stormflows from near-surface lateral flows. The fraction of rapid stormflow response is related inversely to catchment size (the bigger the area, the less the same-day stormflow), vegetation density and the soil's infiltrability, while it responds directly with the degree of urbanisation (the more the urbanisation, the higher the same day response) and catchment slope. It is largely from stormflow events that, for example, reservoirs are filled and peak discharges for selected return periods are computed, while the detachment process in sediment yield generation from a catchment is highly correlated to stormflow volume from an individual event.

Baseflow

Baseflow is the contribution to runoff from previous rainfall events where rainfall has percolated through the soil horizons into the shallow groundwater zones and then contributes as very slow and delayed flow to streams whose channels are "connected" to the groundwater. Baseflows, by constituting the "dry weather" flows which are significant in sustaining flows into the non-rainy seasons, are important for ecological flows and also have different water chemistries to those of stormflows.

Streamflow

Streamflow, within the context of this Report, is the term given to the runoff generated from the catchment under consideration, plus the runoff from all upstream catchments, i.e. it is the integrated flow of the entire upstream area from a point of interest.

What was Assumed when Streamflows were Modelled in this Climate Change Study?

In summary, daily values of streamflows were computed for all Quinary catchments within the Study Area with the *ACRU* simulation model (Schulze, 1995 and updates), the fundamentals of which are summarised in **Chapter 3**. All computations utilised the climate, soils and land cover of the Quinary Catchment Database (Schulze *et al.*, 2010), assuming a baseline land cover of natural vegetation represented by Acocks' (1988) Veld Types, the hydrological attributes of which are described by Schulze (2004), and using soils attributes described by Schulze and Horan (2008).

Annual Streamflows under Historical and Climate Change Conditions, Including Confidence Analysis

In **Figure 8.1** annual accumulated streamflows (mm equivalents) for the lowest flows in 10 years, for median flows and for the highest flows in 10 years are shown in the left hand column for historical climatic conditions, as are the respective ratios of immediate future to present flows (middle column) and a confidence index between present and future flows (right column).

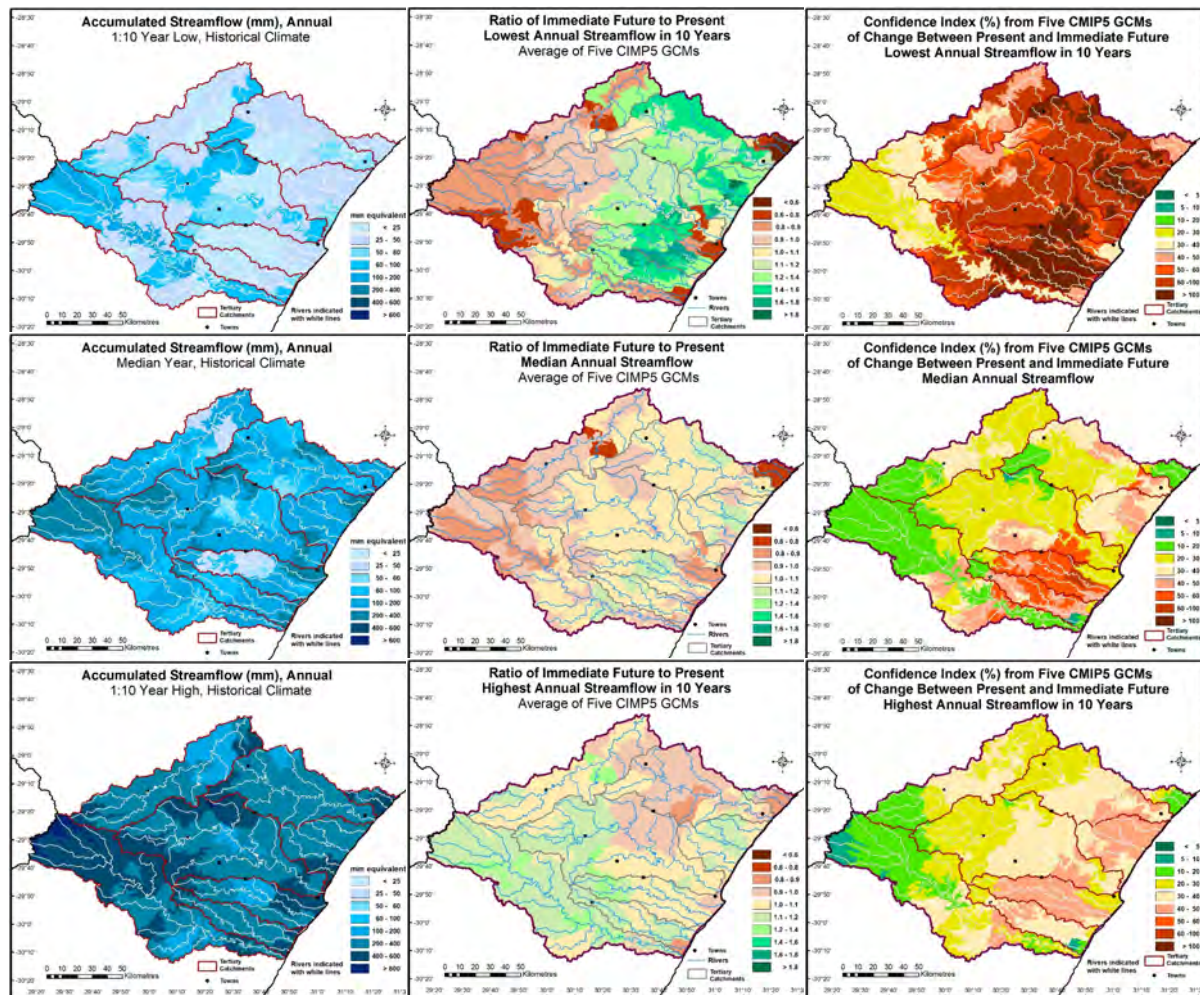


Figure 8.1 Annual accumulated streamflows (mm equivalents) for the lowest flows in 10 years (left column, top map), for median flows (left middle) and for the highest flows in 10 years (left bottom) under historical climatic conditions, as well as the respective ratios of immediate future to present flows (middle column) and a confidence index between present and future flows (right column)

What is clearly visible in the historical maps of accumulated streamflows is the importance of the head water catchments in the higher lying west and along some of the watershed boundaries where higher rainfalls in the upper Quinaries result in higher flows there. In the statistically driest year in 10 flows range from < 25 to 200 mm equivalents, while in median years some Quinaries generate up to 400 mm of streamflow and in wet years streamflows range from 60 to 600+ mm equivalents, with the high flows especially in the upper Mkomaas and the Karkloof areas.

Ratios of immediate future to present flows vary markedly between dry, median and high flow years (**Figure 8.1** middle column of maps). The 1:10 year low flow map shows distinct reductions to 80% and even to only 60% of present flows in the critical source areas of flows in the west, with the degree of reductions somewhat less in median flow years, while flow reductions are projected in the north of the Study Area in wet years. Simultaneously, however, there are projections of streamflow increases into the future in both dry and wet years, at 20 – 40% in parts of the east in dry years and in the south and southwest in wet years.

Confidence in the projections of flow changes into the future display a mixed bag of results, with confidence in results generally low to very low in dry years and acceptable in median flow as well as wet years, but, significantly, with confidence being high in the critical western source areas of water (**Figure 8.1** right hand column).

Seasonal Streamflows under Historical Climatic Conditions

In **Figure 8.2** seasonal streamflows in the Study Area are shown in mm equivalents for historical climatic conditions for spring, summer, autumn and winter for the 1:10 year low flows, median flows and 1:10 year high flows.

Seasonal accumulated streamflows vary widely across the Study Area, ranging from < 10 mm equivalent for 1:10 year low flows in a season to > 400 mm equivalent for 1:10 year high flows in a season. Winter season flows are the lowest for low, median and high flow years, with a carry-over effect of its low flows into spring which, although it receives more rainfall than the winter season, does not necessarily generate much more runoff because of lags in both stormflow and (especially) baseflow generation. Highest streamflows are generated in the summer season from December to February. In all seasons the highest flows occur in the higher lying west, especially in the upper Mkomaas catchment.

Projected Changes in Seasonal Streamflows under Conditions of Climate Change

Seasonal ratios of immediate future to present streamflows in the Study Area for spring, summer, autumn and winter for the lowest flows in 10 years, median flows and the highest flows in 10 years are shown in **Figure 8.3**.

The seasonal ratios display very much a “mixed bag” of results. In years of median flows, these are projected to be reduced in spring, but, significantly in summer which is the season of highest streamflows, an increase in flows is projected, with this trend again being reversed to decreases in flows in autumn and winter. Few trends stand out amongst seasonal changes in low flow and in high flow years

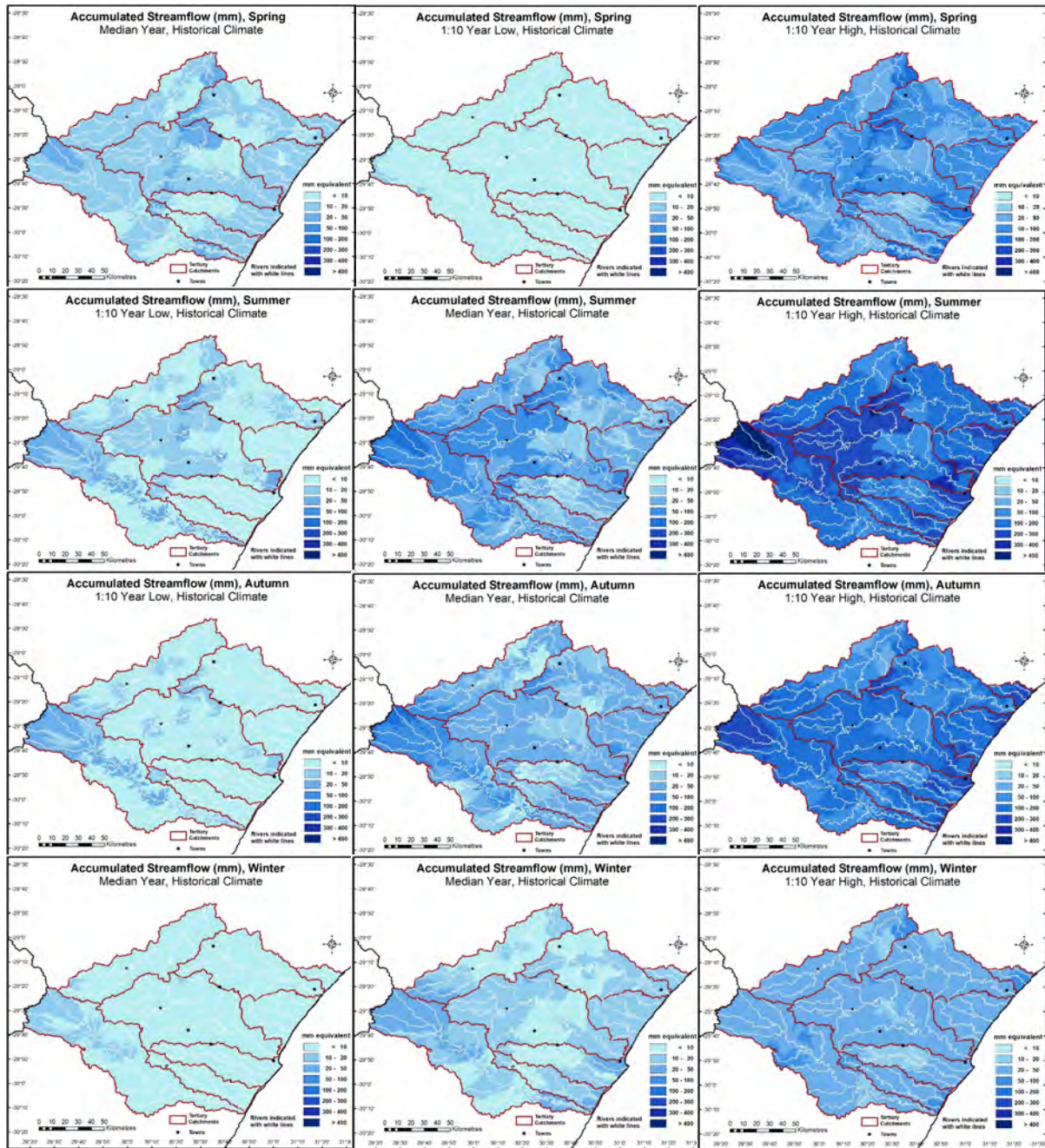


Figure 8.2 Seasonal streamflows in the Study Area under historical climatic conditions for spring (top row of maps), summer (2nd row), autumn (3rd row) and winter (bottom row) for the 1:10 year low flows (left column of maps), median flows (middle column) and 1:10 year high flows (right column)

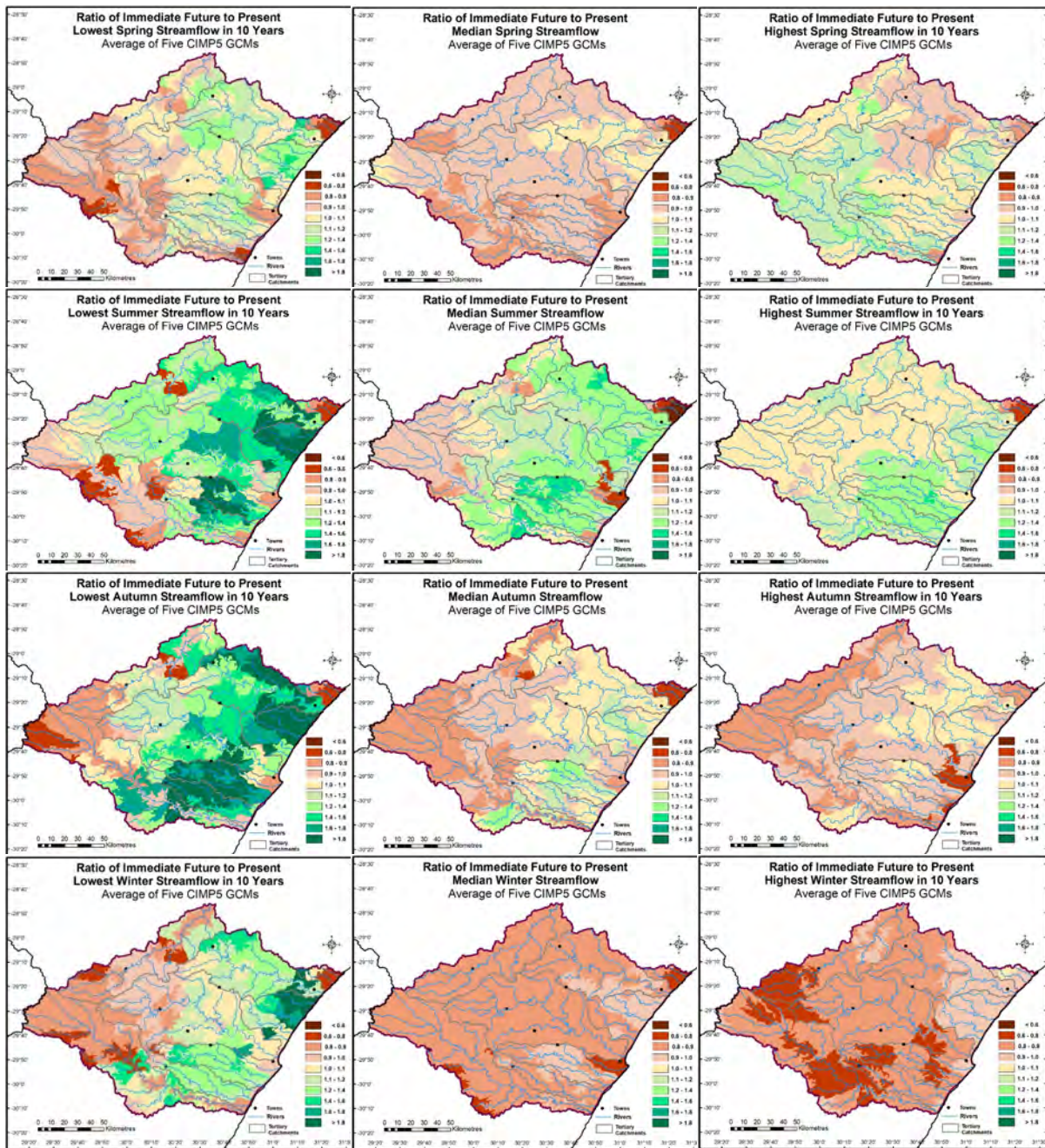


Figure 8.3 Seasonal ratios of immediate future to present streamflows in the Study Area for spring (top row of maps), summer (2nd row), autumn (3rd row) and winter (bottom row) for the lowest flows in 10 years (left column of maps), median flows (middle column) and the highest flows in 10 years (right column)

Confidence in Seasonal Changes of Streamflows from the Present into the Immediate Future

Seasonal confidence indices of changes between present and immediate future streamflows are shown in **Figure 8.4** for the Study Area for spring, summer, autumn and winter for the lowest flows in 10 years, median flows and for the highest flows in 10 years.

Confidence in the results of changes in streamflows projected from the present into the immediate future are generally not high – indicative of the outputs of change derived from the 5 GCMs used being divergent.

Three observations regarding confidence in results may, however, be made, viz.

- Confidence in results increases for all four seasons from low flow to median to high flow years;
- For median flow years, only spring and winter flow changes into the future display relatively high confidences; unfortunately, however, these are the two seasons of lowest flows; and
- Importantly, confidence in flow changes of the mainstems of the major river systems are seen to be considerably higher than changes in the tributaries that feed them.

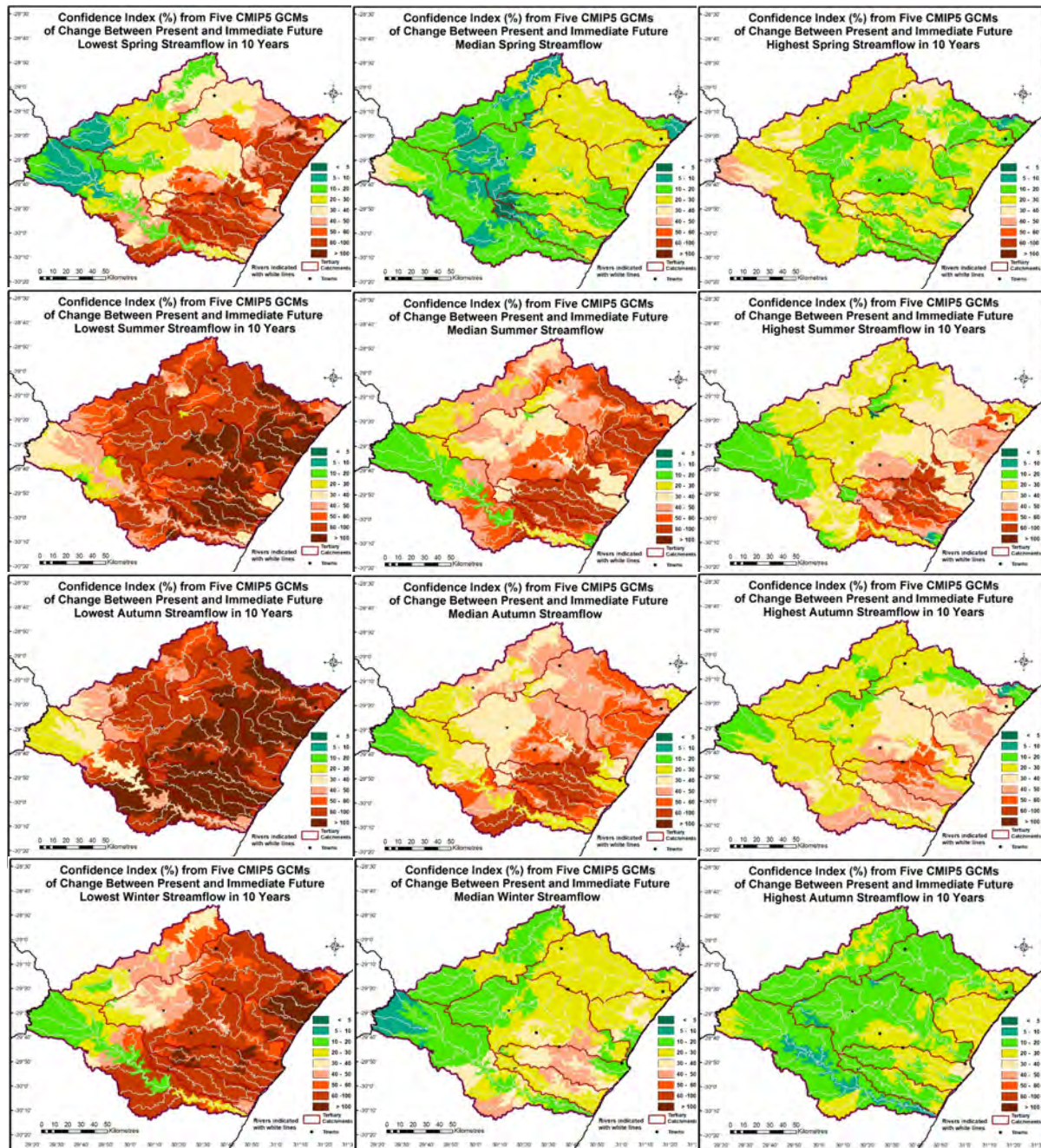


Figure 8.4 Seasonal confidence indices of changes between present and immediate future streamflows in the Study Area for spring (top row of maps), summer (2nd row), autumn (3rd row) and winter (bottom row) for the lowest flows in 10 years (left column of maps), median flows (middle column) and the highest flows in 10 years (right column)

Comparison of Confidence in Rainfall and Streamflow Changes from the Present into the Immediate Future

A visual comparison of the confidence indices of future to present ratio changes of rainfall and streamflow is shown in **Figure 8.5** for changes in medians for the spring, summer, autumn and winter seasons. What is clearly evident in the hydrological “action” seasons of spring and especially summer and autumn is that confidence in the GCM derived changes in rainfall are considerably higher for rainfall than for streamflow. The reasons for this are that any differences in ratio changes among GCMs for rainfall are amplified in the conversion of rainfall changes to streamflow changes.

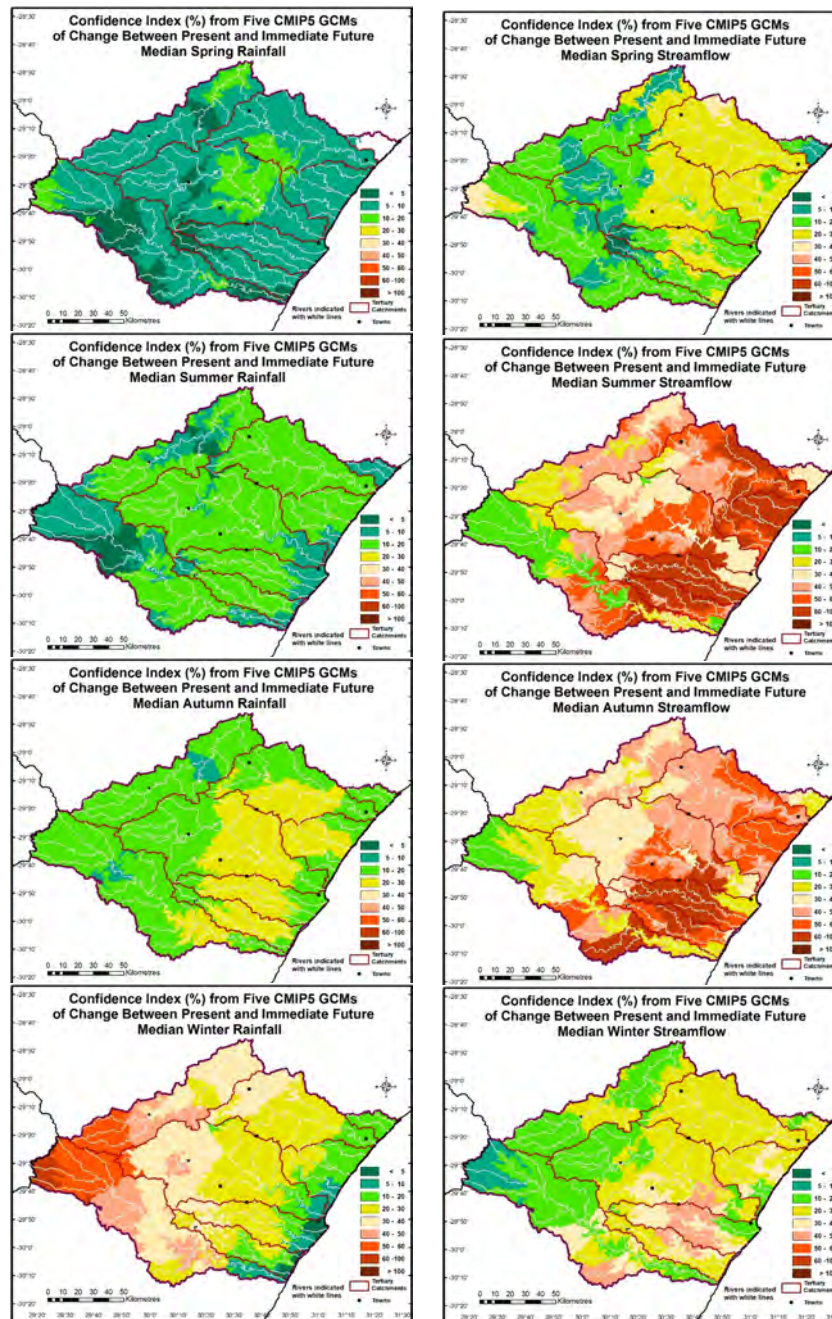


Figure 8.5 Comparison between the seasonal rainfall (left column of maps) and the seasonal streamflow (right column) confidence indices of changes between the present and immediate future in the Study Area for spring (top row of maps), summer (2nd row), autumn (3rd row) and winter (bottom row) for median flows

This finding corroborates the general notion that in climate change studies very high confidence exists in so-called first order changes driven primarily by projected temperature changes, for example, potential evaporation, somewhat lower confidence exists for second order variables such as rainfall, and even lower confidence exists for GCM derived changes in third, or higher, order changes such as streamflow.

Potential Implications to Umgeni Water

The magnitudes of streamflows at annual and seasonal time scales in dry, median and high flow years, and the spatial distributions thereof within an area of interest, lie at the core of the information needs of water resource planners. In this Chapter this information has been derived for the Study Area by hydrological modelling, using both historical climatic conditions and climates projected into the future. While confidence in the changes of streamflows into the future is not as high as one would wish, planners nevertheless have to take cognisance of the findings that projected changes in streamflows within the Study Area for three of the four seasons of the year are negative. Furthermore, for annual streamflows years with median flows are also projected to have lower flows into the immediate future, while for both dry and wet years a mix of reductions and enhancements in streamflows is projected, but with these occurring in different parts of the Study Area.

It is suggested that any water resource related developments into the future take cognisance of the above findings. They also have implications, for example, for irrigators who depend on run-of-river as a source of water.

CHAPTER 9 DESIGN RAINFALL

Background to Design Hydrological Analysis

There are many types of hydraulic engineering and conservation structures (such as culverts, dam spillways or reticulation for drainage) which need to be designed to accommodate floods of a certain magnitude in order to function safely at a given level of risk. Should the structures fail, there are potential economic, environmental and societal consequences. Hence, flood frequency analysis is of great importance (Smithers and Schulze, 2003). Models of peak discharges and flood volumes, however, require inputs of so-called “extreme” rainfall that may be expected to occur only very infrequently, e.g. with recurrence intervals of 2 or 5 or 10 or 20 or 50 or even 100 years, depending on the importance of the structure. Climate change, by expected “energizing” of the earth’s atmosphere through increases in temperature and resultant perturbations to rainfall regimes, including increases to rainfall variability, may lead to increases in the intensity and frequency of extreme rainfall events of both short durations of minutes to hours (not dealt with in this Report) and of longer durations of 1 day or 2 or 3 consecutive day and, with that, associated flooding. These projected increases, if and where they are projected to occur might, consequently, have serious repercussions on the design of hydraulic structures.

Because reliable estimates of flood frequencies based on long time series of good quality observed streamflow data are seldom possible at the site of interest, rainfall based methods of flood frequency estimations therefore usually have to be resorted to. This requires a probabilistic approach to analysing rainfall or simulated streamflow for design purposes. The terms “design rainfall” and “design streamflow” are then used to describe the

- *depth* (i.e. magnitude, in mm or m³) of rainfall or streamflow, for a critical
- *duration* (e.g. 1 day or 2 or more consecutive days), which depends on the size of the catchment, for a desired
- *frequency* of recurrence (e.g. statistically once in 2 or 10 or 20 or 50 or even 100 years, depending on the size and economic importance of the structure), commonly referred to as the return period, and where a return period of, say, 10 years implies a statistical probability of recurrence once in 10 years or 10 times in 100 years, and not that it will recur regularly every 10 years. An estimate of design rainfall can then be used to generate design flood hydrographs when combined with catchment characteristics such as slope, size, land use and soils (Smithers and Schulze, 2003).

This analysis is commonly termed a “DDF” analysis.

This Chapter proceeds first with a summary of the methodology for the computation of long duration (one to three days) design rainfall followed by an interpretation of historical long duration design rainfalls over the Study Area for selected return periods and durations and then an assessment of projected changes in long duration design rainfall with climate change based on outputs from multiple GCMs.

Methodology for the Computation of Long Duration Design Rainfall

In this study historical estimates of design rainfalls of long duration are computed using the 50 year daily rainfall datasets (1950 – 1999) of the Quinary Catchments database (Schulze *et al.*, 2010; Schulze and Horan, 2010). For the climate change assessment, the daily rainfalls for the present (1976 – 2005) and the immediate future (2016 – 2045) scenarios from each of the GCMs used for this study, downscaled to Quinaries, were used. The *annual maximum series* (AMS), i.e. the largest value of rainfall from each hydrological year (October – September) on one day, two consecutive and three consecutive days, was used for further statistical analysis with the General Extreme Value (GEV) distribution applied to determine design rainfalls for selected durations and return periods. The GEV distribution fits most sets of hydrological data.

Design Rainfall under Historical Climatic Conditions

One day design rainfalls (mm) for the 2, 5, 10, 20, 50 and the 100 year return periods (RPs) are shown in **Figure 9.1** for historical climatic conditions. Key features are that the highest design rainfalls for all RPs from 2 to 100 years occur along the coastal zone, with patterns becoming less homogeneous as RPs increase. The range from the 2 to the 100 year one day design rainfall is from 35 to ~ 400 mm. Note that caution should be exercised in interpreting the 100 year RP maps as the record length for computations was only 50 years.

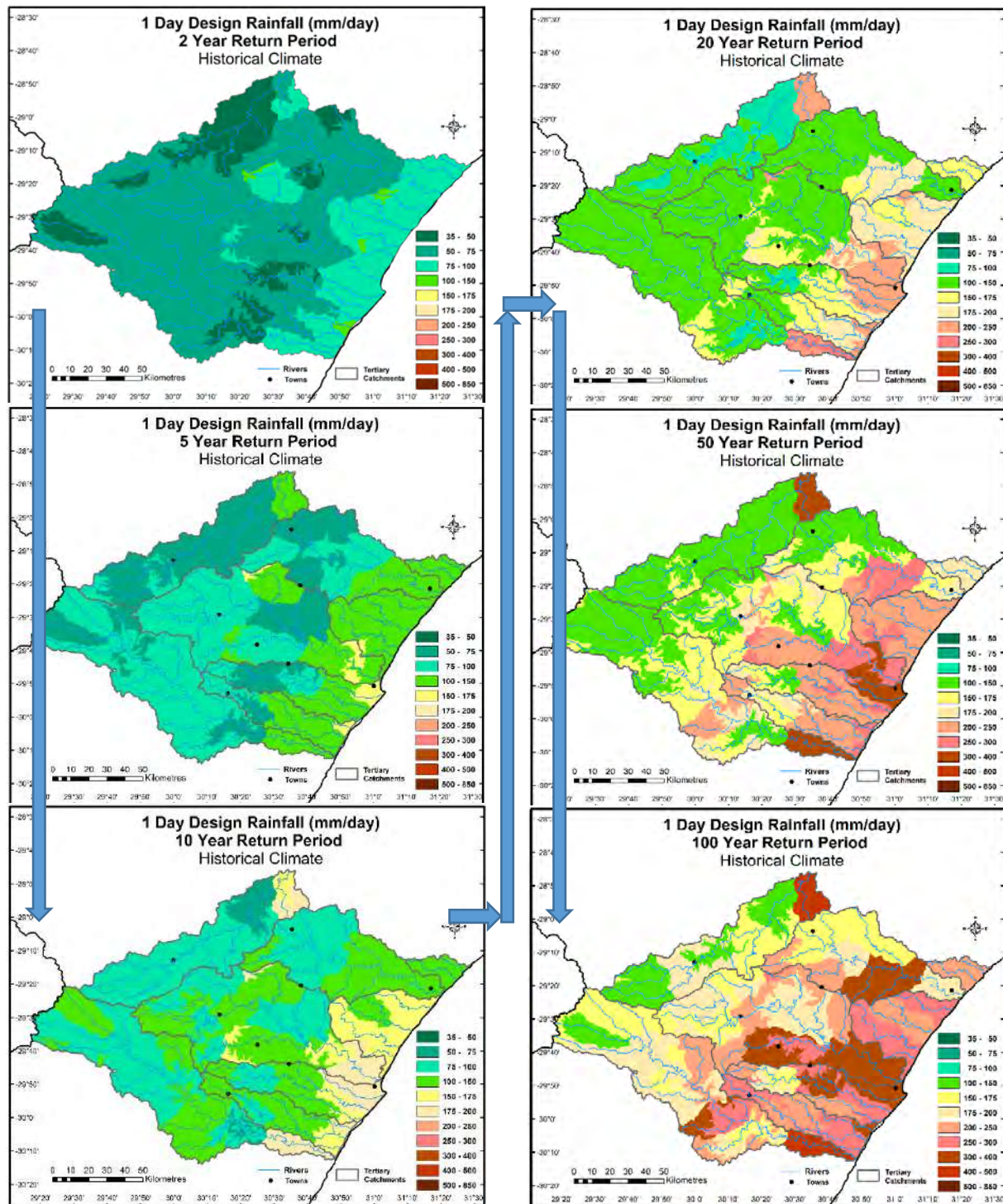


Figure 9.1 One day design rainfall (mm) for the 2 year return period (top left), the 5 year (middle left), 10 year (bottom left), 20 year (top right), 50 year (middle right) and the 100 year return period (bottom right) under historical climatic conditions

When, additionally, considering 2 and 3 consecutive day durations for the key RPs of 2, 10 and 50 years, the highs along the coast are maintained, and the increases across durations (1 to 2 to 3 days; top to bottom maps) and RPs (2 to 10 to 50; left to right maps) are clearly evident, with the highest 3 day 50 year expectation being around 500 mm (**Figure 9.2**).

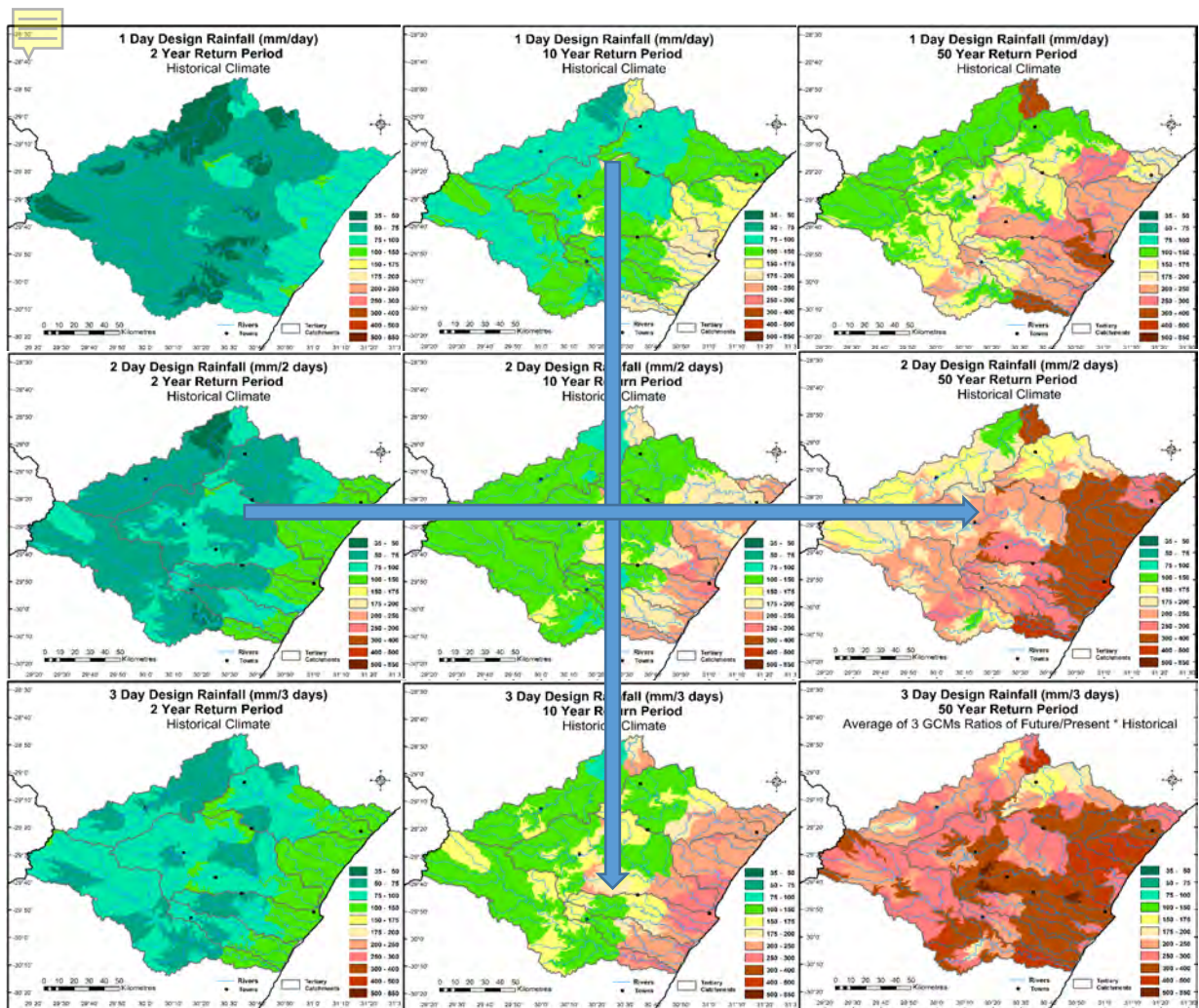


Figure 9.2 Increases in design rainfall magnitudes (mm) from the 1 day to the 2 and 3 consecutive day duration (top to bottom maps) for the 2 year return period, the 10 and the 50 year return periods (left to right maps), under historical climatic conditions

Design Rainfalls in the Study Area under Conditions of Projected Climate Change

In **Figure 9.3** the often-held notion that climatic extremes will of necessity become more extreme everywhere under a more energised atmosphere associated with global warming are dispelled when assessing results from the GCMs that were selected for, and used in, the Study Area. In the maps showing ratios of results between immediate future and present design rainfalls, the shades of red denote projected reductions in design rainfalls with the shades of blue indicating projected increases.

When using ratios of design rainfalls of the immediate future (2016 – 2045) to present (1976 – 2005), results show for both 1 and 3 day durations and for return periods of both 2 and 50 years that parts of the coastal belt display reductions in projected design rainfalls, possibly associated with the moderating influence of an adjacent warm ocean. More importantly, however, is the projected increase of design rainfalls in the interior, by up to 40% (i.e. ratios to 1.4).

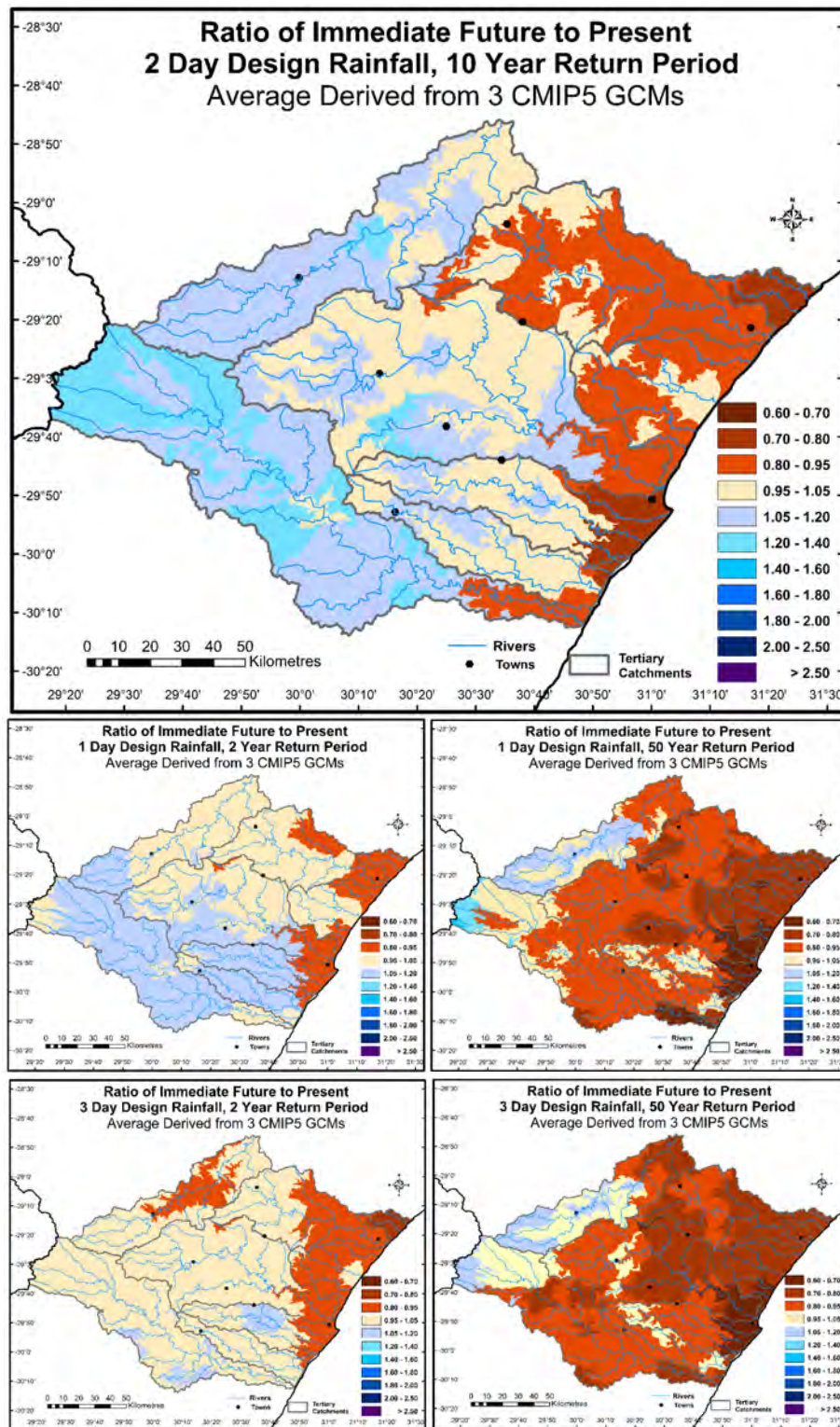


Figure 9.3 Examples of the ratios of the immediate future to present design rainfalls for a range of durations and return periods

Potential Implications for Umgeni Water

A number of points need to be stressed.

- First, it has to be appreciated that design rainfalls under historical climatic conditions were computed from a 50 year record and that statistically, therefore, estimates of the 50 and in particular the 100 year design rainfall values may be somewhat too high or too low.

- Secondly, analyses of multi-day design rainfall (and streamflow) are not part of standard *ACRU* model output, and computations of these were both relatively complex and time-consuming.
- Thirdly, for the prognosis into the future it should be stressed that for both the present and the immediate future only 30 years' of daily rainfall estimates were available and that, therefore, even the 50 year design estimate may be over- or under-estimated.
- Furthermore, out of a suite of 5 CORDEX GCMs made available for the Study, only 3 had adequate overlapping data for both present and immediate future climate scenarios and for both design rainfall and corresponding design streamflows. Confidence in the analyses of design hydrology are therefore not as high as for other hydrological variables.
- Fifthly, design rainfalls under historical climatic conditions, especially along the coastal zone, are already among the highest in South Africa, and that by itself already presents a management challenge.
- Sixthly, if results from the GCMs are considered credible, inland areas are projected to display increases in design rainfall by ~ 20% and even up to 40% into the immediate future only 30 years from now. It would thus be prudent to consider increasing the designs of any infrastructure in the inland, as well as ensuring that any development be kept from the buffer zones of rivers.
- Seventhly, while projections along the coastal zone indicate lower design rainfalls into the future, no lowering of current design standards should be permitted there.
- Finally, design rainfalls are computed for individual Quinary catchments, while design streamflow consider flows from the entire area upstream of a point of interest. Design streamflows are thus anticipated to show somewhat different spatial patterns to those of design rainfalls, as is illustrated in the chapter which follows below.

CHAPTER 10 DESIGN STREAMFLOWS

Design Streamflows: Some Basic Concepts Revisited, and New Ones Addressed

While the basic concepts of design hydrology were spelled out in the previous Chapter, some aspects bear repeating here because the two Chapters are not necessarily always read in conjunction with one another.

Hydraulic engineering and conservation structures such as dams, bridges, culverts and stormwater systems need to be designed to accommodate floods of a certain magnitude and duration in order to function safely at a given level of risk. Climate change, by expected alterations to the temperature and rainfall regimes as well as possible increases in rainfall variability, may lead to changes in the intensity, duration and frequency of extreme rainfall events, and hence of associated flooding. Consequently, this might have serious repercussions on the design of hydraulic structures. Since the failure of such structures can have potential economic, environmental and societal repercussions, including loss of life, it can be appreciated why flood frequency analysis is of great importance (Smithers and Schulze, 2003).

However, reliable estimates of flood frequencies derived from long time series of good quality observed streamflow data are seldom available in South Africa at the site of interest because of the lack of such streamflow data. Therefore, it is common for rainfall based methods of flood frequency estimations to be used. In this study a continuous modelling approach to flood frequency analysis has been used, whereby floods are generated using sequences of daily rainfall which are input into a daily time-step hydrological model. The term “design streamflow” is then used to describe the

- *depth* (i.e. magnitude, in m³ or in mm equivalents) of streamflow, for a critical
- *duration* (in this study of 1, 2 or 3 days’ duration, where such longer durations are important when considering designs on larger catchments, as well as for multiple day flooding and for regional damage assessments), for a desired
- *frequency* of recurrence (e.g. once in 2, or 5, 10 or 20 etc years and longer, depending on the size and economic importance of the structure), where the frequency of recurrence is commonly referred to as the return period (RP) and where a RP of, say, 20 years implies a statistical probability of recurrence once in 20 years or 5 times in 100 years, and not that it will recur regularly every 20 years.

This Chapter commences with a summary of the methodology used in the computation of design streamflows, followed by results, first of design streamflows derived by continuous modelling using historical climate input and thereafter with GCM derived climate values in order to assess possible changes to design floods under projected future climatic conditions.

Summary of the Methodology for Computations of Design Streamflows

As was the case with design rainfall, the General Extreme Value (GEV) distribution was used with the Annual Maximum Series (AMS) to compute the 1, 2 and 3 day design streamflow magnitudes for the 2, 5, 10, 20, 50 and 100 year return periods. The design streamflows were simulated with daily time-step *ACRU* agrohydrological model (Schulze, 1995 and updates; cf. **Chapter 3**) using hydrological attributes of soils (Schulze and Horan, 2008) and baseline land cover (Acocks, 1988; Schulze, 2004) from the South African Quinary Catchments Database (Schulze and Horan, 2010; Schulze *et al.*, 2010). The simulations used daily climate input of 50 years’ duration for a baseline study and two 30 year periods for the present (1976 – 2005) and the immediate future (2016 - 2045) for the climate change impacts study on design streamflows. The daily streamflows at each Quinary’s exit were calculated, with accumulated streamflows utilised as flows cascaded downstream. From these the AMS for the different

durations considered were computed at each Quinary's exit for further analysis with the GEV distribution. Selected results from the design flood analysis are presented below.

Design Streamflows under Historical Climatic Conditions

One day design streamflow (m^3/day) for the 2 year, the 5, 10, 20, 50 and the 100 year return periods are shown in **Figure 10.1** for historical climatic conditions.

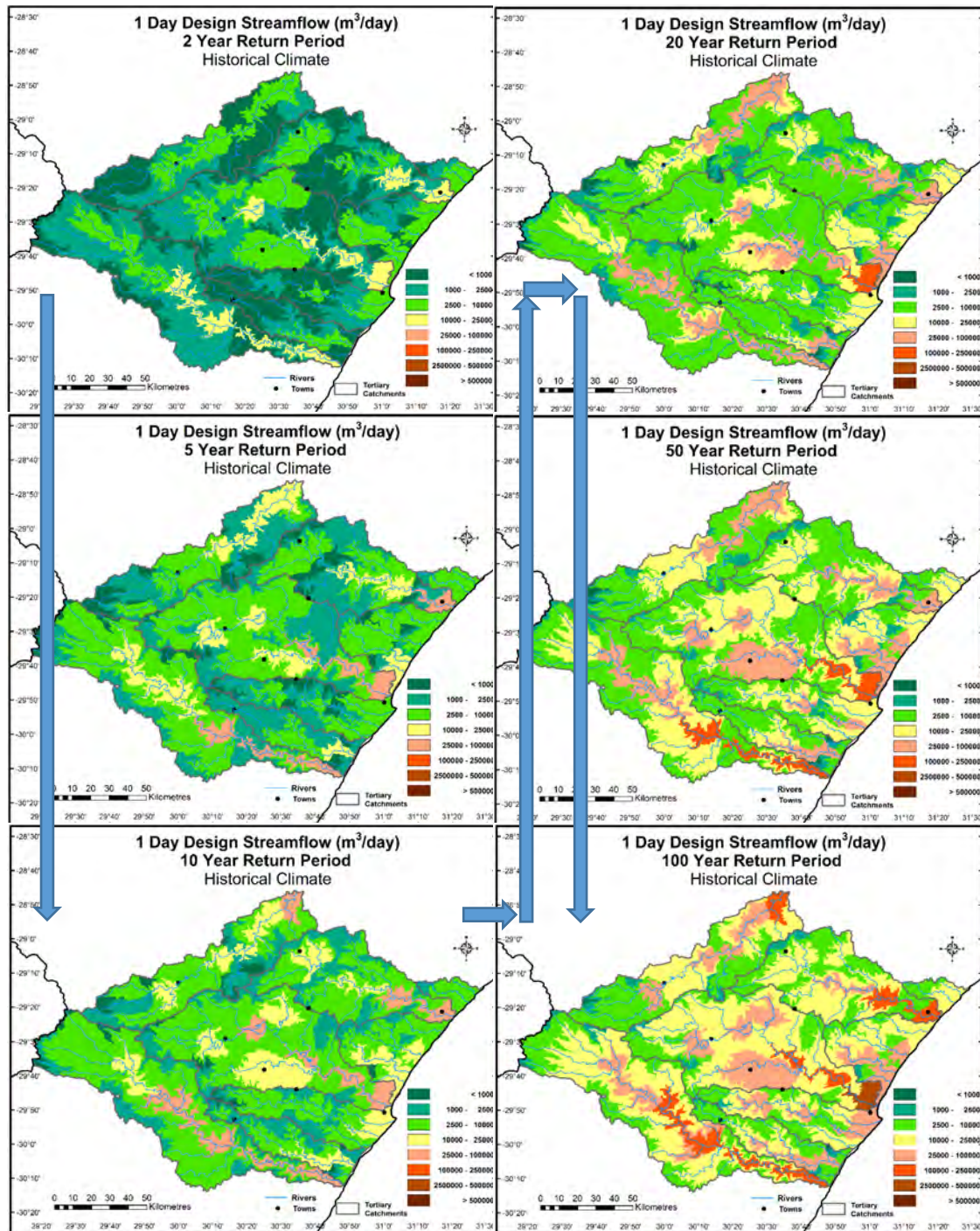


Figure 10.1 One day design streamflow (m^3/day) for the 2 year return period (top left), the 5 year (middle left), 10 year (bottom left), 20 year (top right), 50 year (middle right) and the 100 year return period (bottom right) under historical climatic conditions

A number of features stand out in **Figure 10.1**.

- Firstly, as expected, the design streamflows in the Study Area increase markedly as the return periods increase from the 1 in 2 year event to the 1 in 100 year event.
- Secondly, the class intervals in the map legends increase exponentially because design streamflows are accumulated downstream and not representative solely of the Quinary catchment in which the flows are generated.
- Thirdly, the high design streamflows of the mainstems of the major rivers are clearly evident.
- Fourthly, because of the accumulation of flows, and their being expressed in m^3/day rather than as a mm equivalent, the range of design streamflows from individual small Quinaries to downstream accumulations of relatively large catchments is from $< 1\,000$ to $> 500\,000$ m^3/day – i.e. a 500-fold range.

Expanding the historical assessment from the one day to the 2 and 3 consecutive day design streamflows, **Figure 10.2** shows that for the key return periods of 2, 5 and 50 years, representing respectively annually expected, medium and rare flood magnitudes, the flood magnitudes increase from left to right with RP, as expected, while simultaneously magnitudes increase as the flood duration increases from 1 to 2 to 3 days.

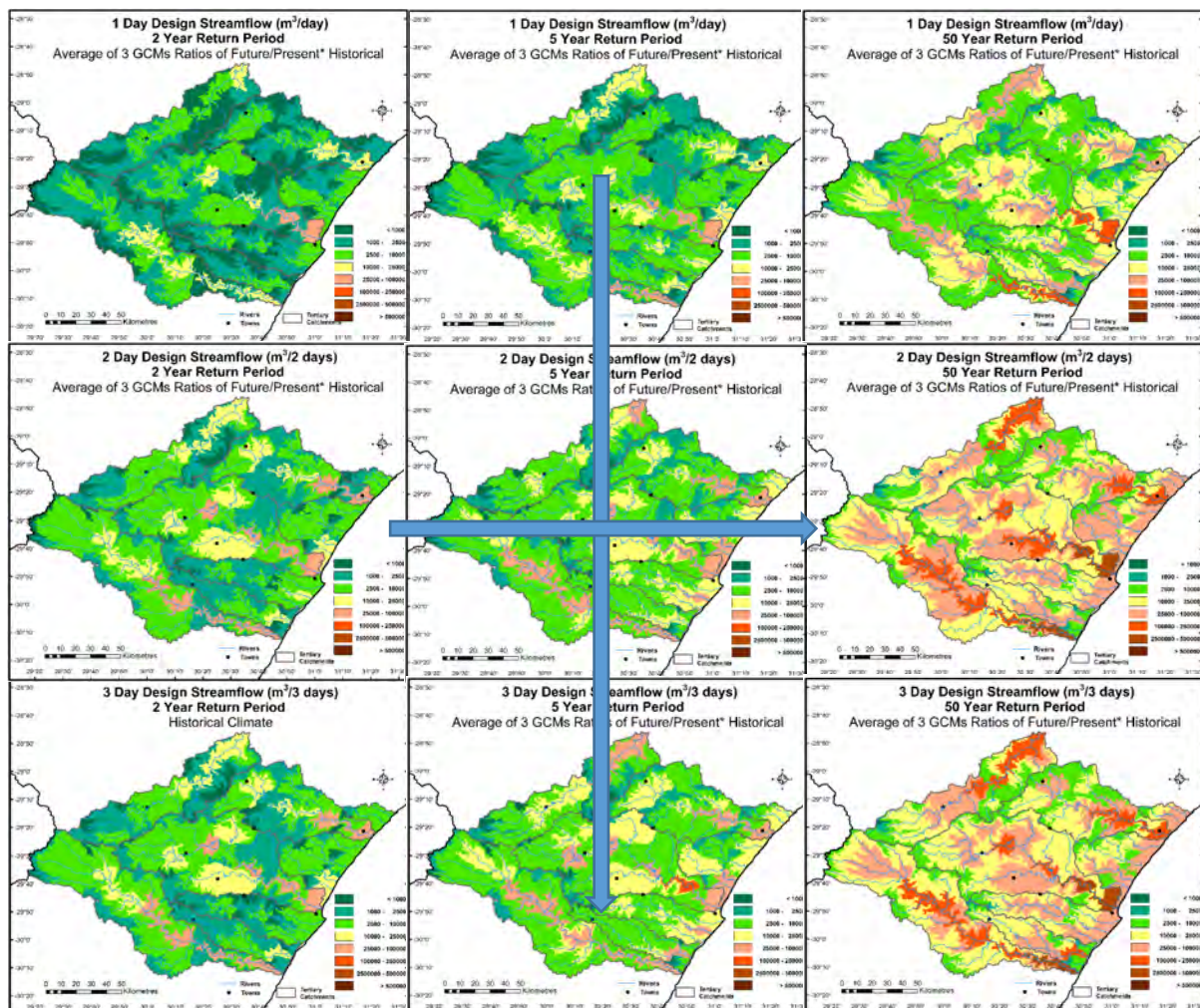


Figure 10.2 Increases in design streamflow magnitudes (m^3/day) from the 1 day to the 2 and 3 consecutive day duration (top to bottom maps) for the 2 year return period, the 5 and the 50 year return periods (left to right maps) under historical climatic conditions

Design Streamflows in the Study Area under Conditions of Projected Climate Change

When expressed as ratio changes between the immediate future (of 2016 to 2045) and the present (of 1976 to 2005), the design streamflows shown in **Figure 10.3** at first glance display a mix of increases (shades of blue, with ratios >1) and decreases (shades of red, with ratios <1). Significant, however, is the observation that for the more critical higher 50 year return periods representing rare floods, the trend is towards a progressively larger proportion of the Study Area to display ratios >1 , i.e. to have more extreme floods projected into the future, this generally by 20% but with significant areas by 40 and even 60%.

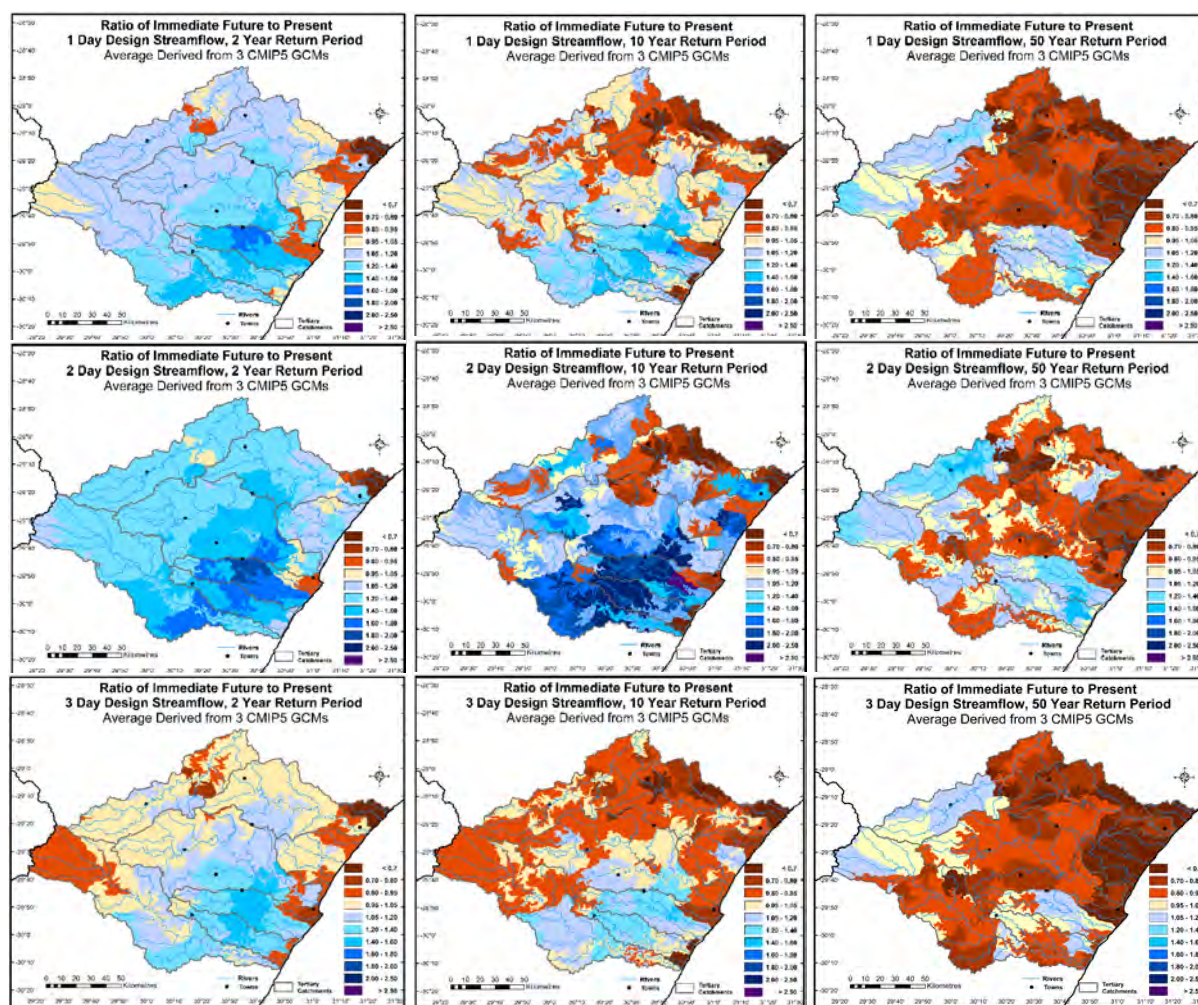


Figure 10.3 Examples of the ratios of the immediate future to present design streamflows for a range of durations and return periods

As already stated in the previous Chapter, it needs to be remembered that for design hydrological analyses only outputs from three GCMs, rather than from five, could be generated for both present and immediate future climatic conditions and that confidence in results is therefore not as high as for that of the other variables.

Comparison between Ratio Changes into the Future of Rainfall and Streamflow

In **Figure 10.4** a visual comparison is made of ratio changes between immediate future and present rainfall and streamflow, in both cases for the 1 and 3 day results for the 2 and 50 year return periods. Some important differences may be observed, viz.

- an amplification of the ratios of design streamflow vs rainfall, with ratios for streamflows being generally higher (i.e. darker shadings) for both negative and positive projected

- changes, illustrating the sensitivity of streamflows to any changes in rainfall; and secondly
- marked spatial differences in patterns between the rainfall and the corresponding streamflow maps, the reasons including that the maximum rainfall for a year does not necessarily produce the maximum streamflow for that year because antecedent soil water conditions as well as soil, slope and vegetation characteristics all modulate the rainfall; and that
- design rainfalls are computed for a specific Quinary catchment while design streamflows are accumulations of everything that occurred upstream, including characteristics of rainfall, slope, soils and land cover.

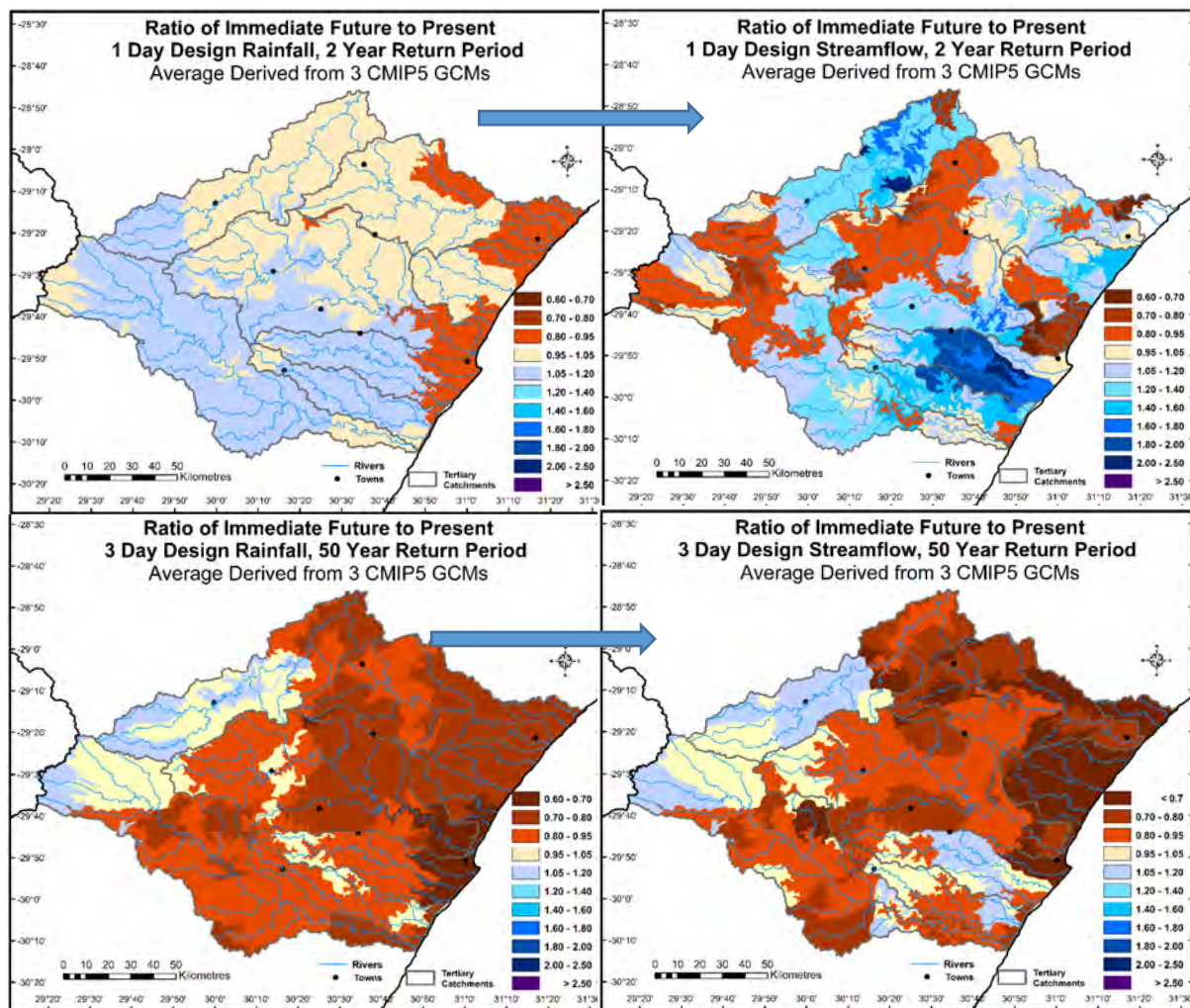


Figure 10.4 Comparison of ratio changes between the immediate future and present rainfall (left column) and streamflow (right column) for selected durations and corresponding return periods

Potential Implications for Umgeni Water

If the above findings, while based on only three CORDEX CMIP5 Global Circulation Models' daily climate outputs from which present and immediate future streamflows were generated by the ACRU model, are considered indicative of the projected impacts of climate change, they then pose new challenges in engineering design, particularly for hydraulic structures on larger catchment areas within the domain of Umgeni Water, as the overall prognosis is for design streamflows to increase.

The approach of using ratio changes of streamflows between a future and a present scenario is considered a valid one, because for any one specific GCM all process representations

remain the same for both future and present scenarios, and a ratio between the sets of results thus largely tends to cancel out any process mis-representations. Furthermore, because in all hydrological simulations the identical model, viz. *ACRU*, was used, any hydrological model process mis-representations tend to cancel out in a ratio approach.

Results nevertheless remain an artefact of *which GCMs* were used, the *number of GCMs* that were used, and the fact that for both present and immediate future GCM scenarios the *record length was only 30 years*, which may be too short to necessarily capture a good representation of “extreme” events.

Pending further analyses of design streamflows, the overall advice to Umgeni Water from outcomes of this Study would be to err on the conservative side by adding a climate change related margin of safety to all new hydraulic structures, even where results show no enhancement to design flows due to climate change. The reasoning for the latter statement is that structures are designed to operate safely into an era well beyond that of a future in which hydrologically stationarity of the past can be assumed.

CONCLUDING THOUGHTS

The concluding thoughts which follow below essentially summarise the implications of the various findings to Umgeni Water.

In regards to **reference potential evaporation**, with historical annual values already high at around 1 500 mm and up to 2 000 mm, and with climate projections into the immediate future of the 2030s and 2040s showing annual increases between 60 and 100 mm, which are equivalent to 2 – 3% along the coast to ~ 10 % in the higher lying west, and with seasonal E_r ranging from 200 mm in winter up to 600 mm in summer, potential evaporation constitutes an unavoidable loss to Umgeni Water from dams, wetlands and riparian zones. This loss will be exacerbated into the future beyond the 2040s. Additionally, all else remaining the same, E_r increases will result in soils drying out more rapidly in future, with this having potential implications on runoff production. Furthermore, irrigation water demands will be higher, affecting Umgeni Water both by abstractions from dams being increased, and by river flows being reduced where irrigation is from run-of-river.

In the case of **annual and seasonal rainfalls**, seasonal confidence indices of the projected changes between present and immediate future rainfalls in the Study Area were assessed. Two observations stood out, viz. that for a given season confidence in results is lowest in dry years and highest in wet years and, secondly, that confidence in results varies with season, being lowest in winter, second lowest in autumn and highest in spring.

Dry spells of short and medium duration are a concern to water resource managers as these imply increases in irrigation water requirements and reductions in runoff. The projections of more dry spells of 2 and 3 consecutive months' duration over the next 30 years will constitute a further concern to Umgeni Water as they are shown, according to the GCMs used, to occur in the higher lying western regions which are source areas of major rivers in the Study Area.

In the **wet spell analysis**, the projected reduction per annum in wet spells in the west, especially those of 2 and 3 months' duration, implies fewer runoff producing events in a region of the Study Area that is a critical source area of water. Furthermore, this reduction in wet spells will imply increases in irrigation water requirements likely to be experienced there in future. These findings are offset by projected increases in wet spells in the eastern two-thirds of the Study Area. Arguably the biggest concern to Umgeni Water in the dry and wet spell analyses is, however, the "double whammy" in the west of the Study Area where both *increases* in dry spells and simultaneously *decreases* in wet spells are projected by the CORDEX GCMs utilised in this Study. Again, this finding is important since the west is a critical source area of water to the region.

Magnitudes of **streamflows at annual and seasonal durations** in dry, median and high flow years, and the spatial distributions thereof within an area of interest, lie at the core of the information needs of water resource planners. For the Streamflow chapter these core information needs had been derived for the Study Area by hydrological modelling with a process based daily time step model, using both historical climatic conditions and climates projected into the future. While confidence in the changes of streamflows into the future were found not to be as high as one would have wished, planners nevertheless have to take cognisance of the findings that projected changes in streamflows in the Study Area for three of the four seasons of the year are negative, i.e. flow reductions may be expected. Furthermore, for annual streamflows years with median flows are also projected to have lower flows into the future, while for both 1:10 year dry and wet years a mix of reductions and enhancements in streamflows is projected, but with these in different parts of the Study Area.

From the findings on **design rainfall**, a number of points were highlighted.

- First, it had to be appreciated that design rainfalls under historical climatic conditions were computed from a 50 year record and that statistically, therefore, estimates of the 50 and in particular the 100 year design rainfall values may be somewhat too high or too low.
- Secondly, analyses for multi-day design rainfall (and streamflow) were not part of standard *ACRU* model output, and computations of these were both more complex and time-consuming.
- Thirdly, for the prognosis into the future it should be stressed that for both the present and the immediate future only 30 years' of daily rainfall estimates were available and that, therefore, even the 50 year design estimate may be over- or under-estimated.
- Furthermore, out of a suite of 5 CORDEX GCMs made available for the Study, only 3 had adequate overlapping outputs for both design rainfall and corresponding design streamflows for both present and immediate future climate scenarios. Confidence in the analyses of design hydrology is therefore unlikely to be as high as for other hydrological variables.
- Fifthly, design rainfalls under historical climatic conditions, especially along the coastal zone, are among the highest in South Africa, and that by itself already presents a management challenge.
- Sixthly, if results from the GCMs are considered credible, inland areas are projected to display increases in design rainfall by ~ 20% and even up to 40% into the immediate future only 30 years from now. It would thus be prudent to consider increasing the designs of any infrastructure in the inland, as well as ensuring that any development be kept from the buffer zones of rivers.
- Seventhly, while projections along the coastal zone indicate lower design rainfalls into the future, no lowering of design standards should be considered.
- Finally, design rainfalls were computed for individual Quinary catchments, while design streamflow considers flows from the entire area upstream of a point of interest. Consequently, design streamflows were thus anticipated to display somewhat different spatial patterns to those of design rainfalls. This proved to be the case.

In the final technical chapter, **design streamflows** were assessed under historical and projected climatic conditions.

- Findings, while based on only three CORDEX CMIP5 Global Circulation Models' daily climate outputs from which daily present and immediate future streamflows were generated by the *ACRU* model, were nevertheless considered indicative of the projected impacts of climate change.
- The findings pose new challenges in engineering design, particularly for hydraulic structures on larger catchment areas within the domain of Umgeni Water, as the overall prognosis was for design streamflows to increase.
- The approach of using ratio changes of streamflows between a future and a present scenario was considered a valid one, because for any one specific GCM all process representations remained the same for both future and present scenarios, and a ratio between the sets of results would thus largely tend to cancel out any process mis-representations. Furthermore, because in all hydrological simulations the identical model, *viz.* *ACRU*, was used, any hydrological model process mis-representations were thus considered to cancel out in a ratio approach.
- Results nevertheless remain an artefact of *which* GCMs were used, the *number* of GCMs that were used, and the fact that for both present and immediate future GCM scenarios the *record length* was only 30 years, which may be too short to necessarily capture all large events.

Pending further analyses of design streamflows, the overall advice to Umgeni Water from outcomes of this Study would be to err on the conservative side by adding a climate change related margin of safety to all new hydraulic structures, even where results show no enhancement due to climate change. The reason put forward for this is that structures are

designed to operate safely into an era well beyond that of a future in which hydrologically stationarity of the past can be assumed.

In the final analysis, it is suggested that any water resource related developments into the future take cognisance of the above findings.

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