Managing climate risk for agriculture and water resources development in South Africa: Quantifying the costs, benefits and risks associated with planning and management alternatives

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Abstract

The Western Cape is an extremely important region to the economic development of South Africa. It is one of South Africa's most valuable agricultural production regions. Almost all of the land that is farmed in this region is under irrigation. The population in Metropolitan Cape Town and a number of smaller cities in the region is growing rapidly. As this has happened, the demand for water in Metropolitan Cape Town has increased around 4 per cent per year over the last decade (Louw & Van Schalkwyk, 2002). Against this backdrop of rapid water demand growth and increasing competition between agricultural and urban water users, are the issues of local climate variability and climate change.

The Western Cape is one of the few regions to demonstrate consistent projections of changes in climate under standard (SRES) Intergovernmental Panel on Climate Change (IPCC, 2007) forcing scenarios. These scenarios suggest a future reduction in available rainfall, which will exacerbate an already water-stressed region.

An integrated modelling framework to investigate the costs and benefits of various adaptation strategies towards climate change was developed. The integrated framework includes downscaled climate change data, hydrological data, bulk infrastructure simulation and agricultural and urban water demand modules that maximises the economic value of the net returns to water from agricultural and urban water users on a monthly basis over a 20-year (or longer) time horizon. The modelling results demonstrate how the integrated framework can contribute towards improved decision making in the planning and management of climate risk.

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1. INTRODUCTION

In recent years, the economy of the Western Cape region has received an stimulus from tourism, with visits to Cape Town from Europe, Asia, and North America growing at an annual rate of over 10 per cent. Growth in the tourism industry has created a boom in the local building industry and this growth has been supplemented by equally rapid growth in the construction of vacation and retirement housing. Not surprisingly, the population in Metropolitan Cape Town and a number of smaller cities in the region is also growing rapidly, swelled by the demand for jobs in the construction and services industries related to tourism. Also, after the 1994 election of the first real democratic elections in South Africa, all of the sanctions imposed on the previous regime were removed (Jooste & Aliber & Van Schalkwyk, 1999). This opened the international market for agricultural markets and resulted in substantial growth in especially wine and fruit exports for the Western Cape region. The South African Marketing Act, which regulated marketing through agricultural marketing control boards, was repealed in 1997 and this provided an additional stimulus for entrepreneurs and growth in agricultural exports (Groenewald, 2000) from the Western Cape. A secondary impact of these events was a significant growth in the demand for irrigation water in the region. Against this backdrop of rapid water demand growth and increasing competition between agricultural and urban water users, are the issues of local climate variability and climate change.

An integrated modelling framework to investigate the costs and benefits of various adaptation strategies towards climate change were developed. The modelling framework is presented together with results which illustrate the impact on irrigation farming and food security. The paper concludes with the implications for maintaining /improving productivity and profitability.

2. BASIC DECRIPTION OF THE MODEL

For the sake of brevity the mathematical model is not included here but is available from the authors. The model is complex in order to simulate the complexity of the supply infrastructure and the demand sectors as close as possible. During 2005 a case study within the Assessment of Impacts and Adaptations to Climate Change programme (AIACC) was devoted to developing an integrated climate-hydrology-economic model the Berg River Dynamic Spatial Equilibrium Model (BRDSEM). The Berg River Basin is located northeast of Metropolitan Cape Town. BRDSEM was developed specifically for this region to help water policy-makers and planners to examine the physical and economic impacts of rapid population growth and climate change; to assess the physical and economic benefits and costs of structural and non-structural measures for coping with both these problems; and to estimate the economic value of the physical damages that could be avoided by these options (Callaway & Louw & Hellmuth & Nkomo and Sparks, 2008). The BRDSEM model was extended and improved during 2009 to 2011 (Louw & Johnston & Tadros & Schulze & Lumsden & Callaway and Hellmuth, 2012) and the current modelling framework (see Figure 1) consists of three modules. These are:

- The regional climate change module – downscaling of Global Climate Models (GCM's). Statistical downscaling utilises statistical methods to approximate the regional scale response to the large scale forcing. Various methods have been developed, including the SOMD (Self Organising Map based Downscaling) developed at the University of Cape

Town which was used in this study. Details of the method can be found in Hewitson and Crane (2006).

- A hydrological module. Using the Agricultural Catchments Research Unit (*ACRU)* model *(*Schulze, 1995; Smithers and Schulze, 2004) to estimate incremental runoff at specific locations within the study region.
- A dynamic programming module with three components:
  - Regional farm models (21 farms) to simulate the demand for agricultural water under different climate regimes (scenarios).
  - An intertemporal spatial equilibrium model to simulate the bulk water infrastructure (main storage dams, canals, pipelines and tunnels) and farm dams.
  - An urban demand module to simulate the demand for urban water use sectors.

In addition the integrated framework also makes provision for external inputs such as:

- Policies, plans and technology options for increasing water supplies
- Reducing water demand through water demand management options.

The output of the model consisted of:

- Benefits and costs of structural and non-structural water management options
- Water values and water tariffs (prices)
- Reservoir inflows, storage, transfers, releases and evaporation
- Water use by the urban and agricultural water use sectors.

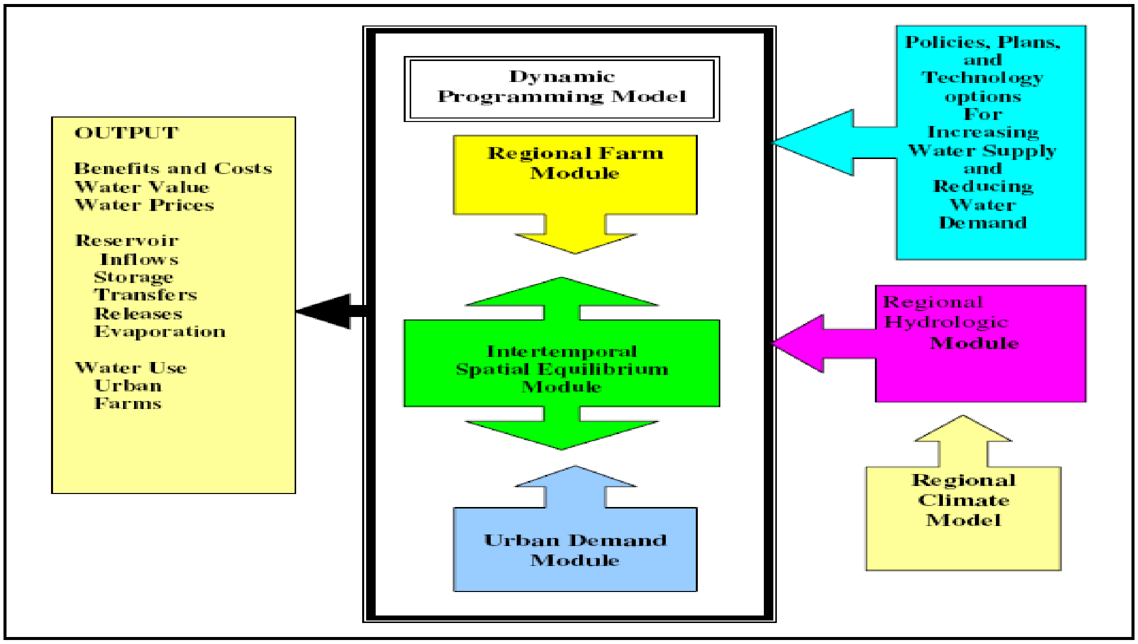


Figure 1: **Schematic diagram of the integrated modelling framework**

The model is an optimisation model that ***maximises the economic value of the net returns to water from urban and agricultural water users on a monthly basis over a thirty-year (or longer) time horizon***. Runoff nodes, storage and farm reservoirs and water diversions are linked together by spatially differentiated flows consistent with basin hydrology. The model also maintains dynamic storage balances in all reservoirs. Urban water demand is characterised by monthly demand functions. Regional dynamic linear programming (DLP) farm models were developed to simulate the demand for irrigation water. Monthly runoff, reservoir evaporation and crop water use adjustments in the optimisation model were linked directly to a spatially-differentiated water balance model that is, in turn, linked to a model that downscales climate data from Global Climate Model (GCM) scenarios to the regional level.

3. DATA USED

The resolving scale of GCMs has improved significantly in the last 10 years with many state of the art GCMs able to resolve at a scale of around 100 km. Downscaling is the concept based on the assumption that local scale climate is largely a function of the large scale climate modified by some local forcing such as topography. Downscaled climate data (rainfall and temperature) was obtained from the **Climate Systems Analysis Group at the University of Cape Town**. This data was then feed into the ACRU model by the School of **Bioresources Engineering & Environmental Hydrology at the University of KwaZulu-Natal**. The output data from ACRU (evaporation coefficients, runoff and a crop water adjustment coefficient) is then used as input into the dynamic spatial equilibrium model with embedded regional dynamic linear programming farm models to simulate the demand of agricultural water and urban water demand functions to simulate the demand for urban water. **Farm data was obtained through a comprehensive farm survey** on more than 400 farms in the region. This data was then processed into a format to be used to construct regional farm models. Urban water demand time series data was obtained from the **Cape Town Water Utility** and used to construct quadratic demand functions for the urban sector. Finally, the **Department of Water Affairs in the Western Cape** provided all the technical data (capacities of dams, pipelines, canals, pumping and release capacities and operating rules) to simulate the bulk water infrastructure and operating rules.

4. DOWNSCALING RESULTS

From the model downscaling the map for winter and summer and shown below in Figure 2 and Figure 3 respectively.

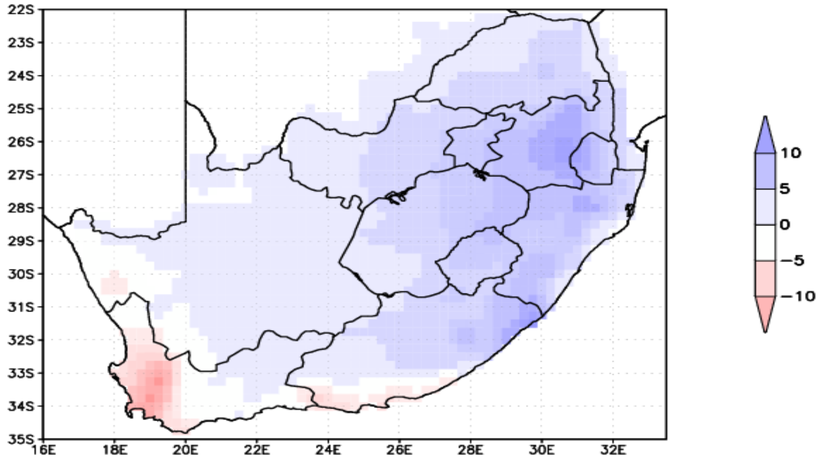


Figure 2: Winter (JJA) rainfall anomaly projections (2046-2065) for SA

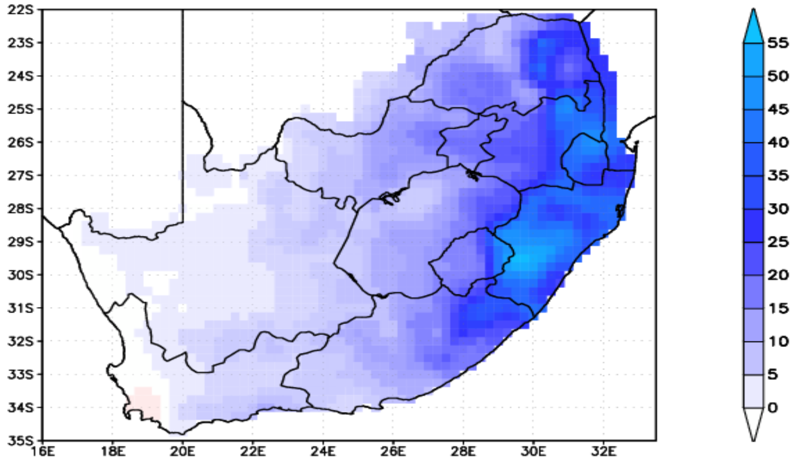


Figure 3: Summer (DJF) rainfall anomaly projections (2046-2065) for SA

These seasonal results were further analysed to produce monthly figures for the rainfall anomalies for the Western Cape region. The 6 downscaled outputs for the winter rainfall season can be seen in Figure 4. These were sorted into “dry” or Low Scenario, and “wetter” or High Scenario for use in the hydrological models.

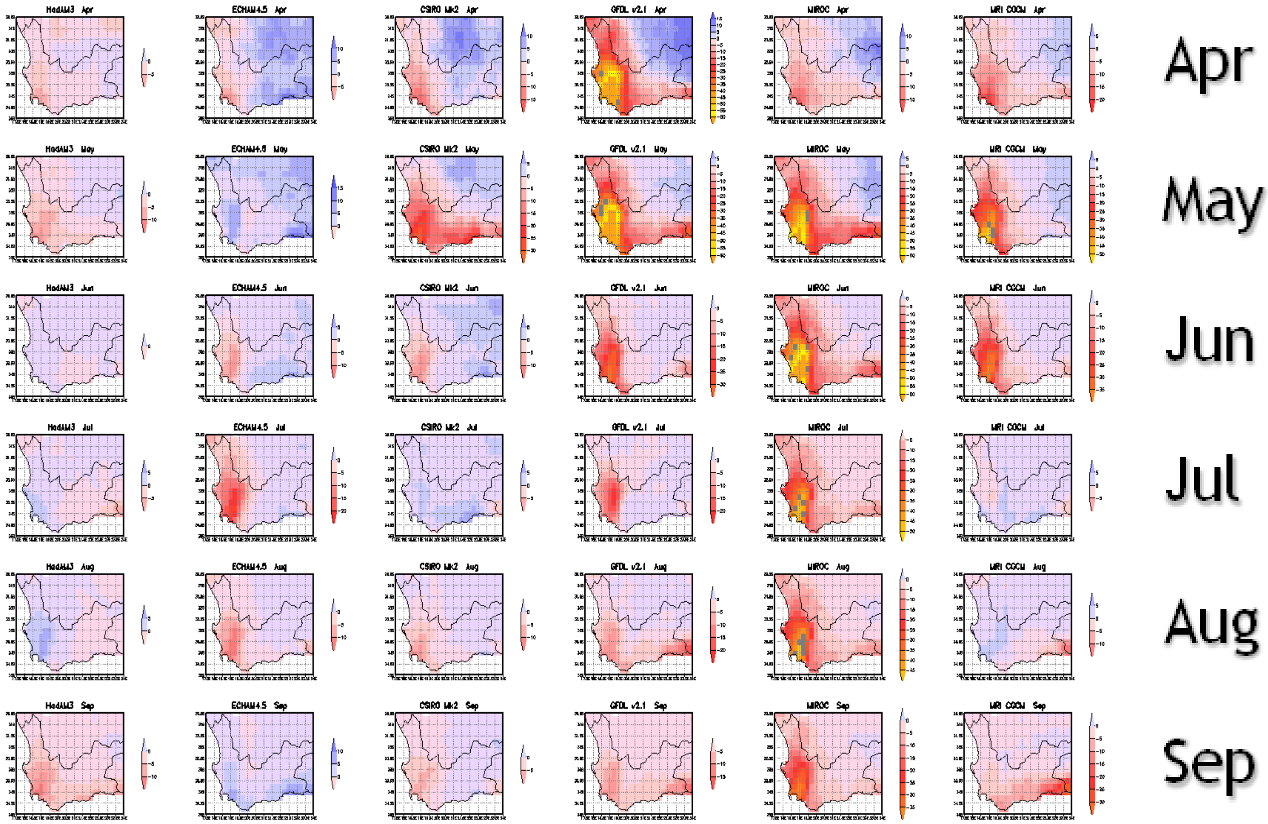
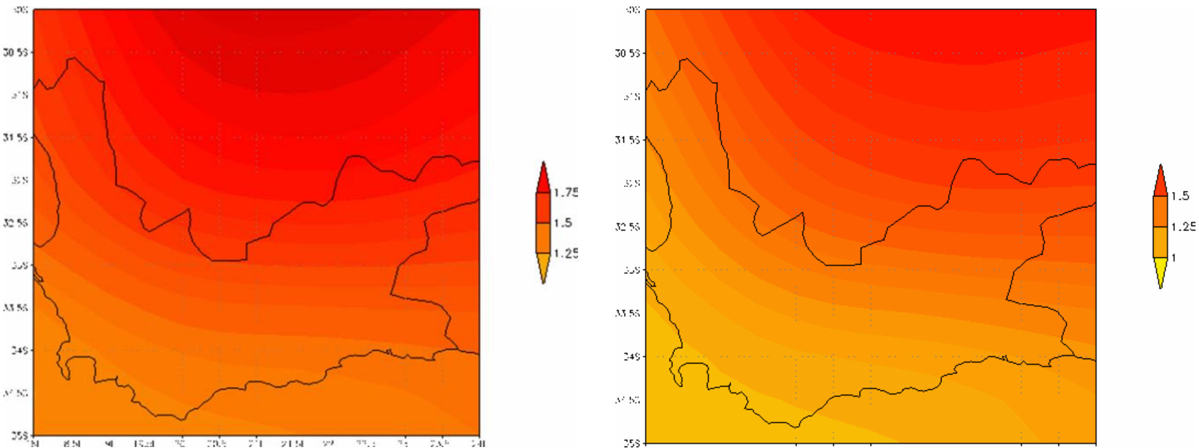


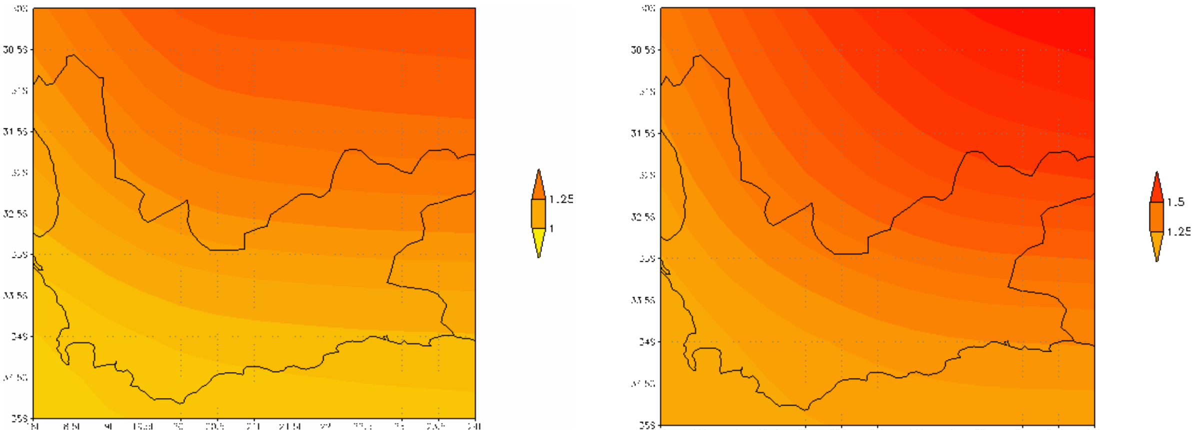
Figure 4: Projected changes in rainfall pattern and magnitude; Monthly Total anomalies. Downscaling to a 0.1° precipitation grid.

A glance at the results shows that there is some variation in the model output over the study area. While many models show a drying, there are more than a few that display a slight wetting. The distinction of High and Low scenarios therefore gives the hydrological model a range of possible rainfall outcomes.

The temperature projections (which were not downscaled for the GCM) and are shown in Figure 5, display a general increase in temperatures of the entire study region. The result of this general increase would be higher evaporation possibly resulting in lower runoff.



(a)DJF (b)MAM



(c)JJA (d)SON

Figure 5: Projected temperature anomalies (a) DJF (b) MAM (c) JJA and (d) SON

It is clear from the climate change downscaling results that it can be expected that there is more uncertainty in rainfall predictions compared to temperature. There is almost certainty that the average temperature in the Western Cape is going to increase with approximately 1-1.5 °C. However, some models show an increase in rainfall and other a decrease in rainfall.

5. HYDROLOGICAL MODELLING RESULTS

The climate projections applied in hydrological modelling were limited to a “High” (ECHAM5/MPI-OM) and “Low” (IPSL-CM4) GCM (based on projected changes in annual rainfall) to limit the number of hydrological and economic simulations to a manageable level. The present period (Base) selected for hydrological and economic modelling was shortened to 20 years (from the number of years available in the climate projections) to ensure that the present (Base) and near/distant future periods were of the same length (for comparison purposes).

For the purpose of this paper only the distant future (2046 – 2065) is presented. Figure 6 shows the projected impact of climate change in the distant future on the standard deviation of annual rainfall, reference potential evaporation and runoff at subcatchment level for the UCT High and UCT Low scenarios. Analysis of Figure 6 reveals widespread reductions in annual variability of rainfall, potential evaporation and runoff for the High scenario. For the Low scenario, a neutral to increasing pattern in variability is mostly evident, except for the upper and mid sections of the Berg River basin which shows decreases in rainfall and runoff variability.

The impacts of climate change are more evident in the distant future as the effects of global warming gain momentum. This is seen in the differences between the High and Low scenarios of the distant future (in terms of rainfall and runoff. It is also seen in changes in potential evaporation (driven by increasing temperatures) where no change is projected in the near future, but changes of up to 10% are projected for the distant future.

In general the results show that where means of rainfall (and runoff) increase, the variability decreases. This implies that under wetter conditions, rainfall becomes less erratic. ***The divergence in runoff results between High and Low scenarios for the distant future implies greater uncertainty which must be incorporated in planning decisions. In contrast, there is much greater certainty regarding the changes expected for temperature and potential evaporation***.

This implies that decisions related to changes in temperature and potential evaporation can be made with greater confidence, although for many decisions there is a co-dependence with water availability which needs to be considered.

A shortcoming of the research is that more GCMs were not considered in the hydrological and economic simulations (this limitation was due to time and computing constraints), as this may have given an indication as to whether there is a greater tendency towards either the High or Low scenarios in terms of water availability. In this context it follows that ‘no’ or ‘low regret’ adaptation options are the most pragmatic.

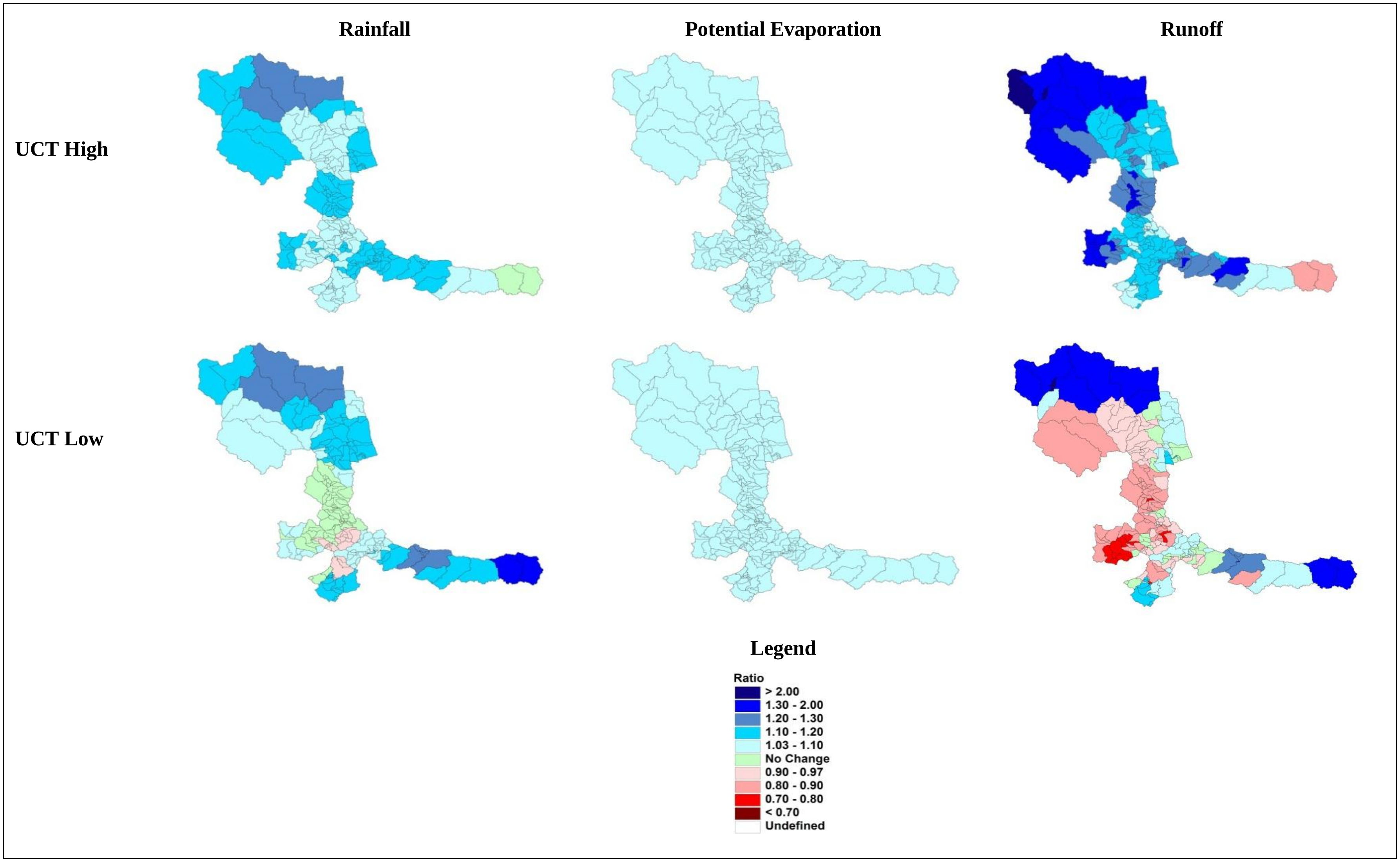


Figure 6: Ratios of distant future to present mean annual precipitation, potential evaporation and runoff for the UCT High and UCT Low scenarios

6. ILLUSRATIVE SCENARIOS ANALYSED WITH INTEGRATED MODELLING FRAMEWORK

Several climate change adaptation scenarios were analysed for this project which are contrasted to a base scenario. However, for the sake of brevity only **two sets** of results are presented in this paper. These are:

- Set 1: comparing the base analysis (no adaptation) for all the climate change scenarios which were discussed earlier in this paper:
  - UCT Base Low (simulation based on historical climate data from 1971-1990) – on average this simulation shows a "dry" future.
  - UCT Base Low Future (same as UCT Base Low except for future runoff and crop water use for the period 2046 to 2065)
  - UCT Base High (simulation based on historical climate data from 1971-1990) – on average this simulation shows a "wet" future.
  - UCT Base High Future (same as UCT Base Low except for runoff and crop water use
- Set 2: An increase in farm dam capacity of 20% as an adaptation strategy to climate change. The relative changes compared to the base analysis are presented and discussed.

Due to the huge volumes of information generated in the course of the modelling, the results are presented somewhat selectively. All the results are described in the following sequence:

- Irrigation intensities (optimal, supplemental, deficit irrigation and dry land)
- Crop combinations
- Agricultural water demand
- Average urban water demand per annum
- Main dam water storage per month
- Income from water sales to the urban sector and water supply cost to the sector.
- Total cost of agricultural water
- Total Net Disposable Farm Income
- Capitalised marginal value of irrigation water
- Average annual Incremental Runoff
- Average annual agricultural and urban water demand and the average annual main dam storage.

6.1 COMPARISON OF BASE CLIMATE CHANGE SCENARIOS

Figure 7 shows the average annual incremental runoff (at all sites) for the different climate scenarios. It is clear that there is no significant difference between the UCT Base Low and the UCT Base Future Low Scenarios. However, the runoff is significantly higher in the UCT Base High and even higher in the UCT Base Future High scenarios. It is important to take note of this since it explains most of the results which are discussed.

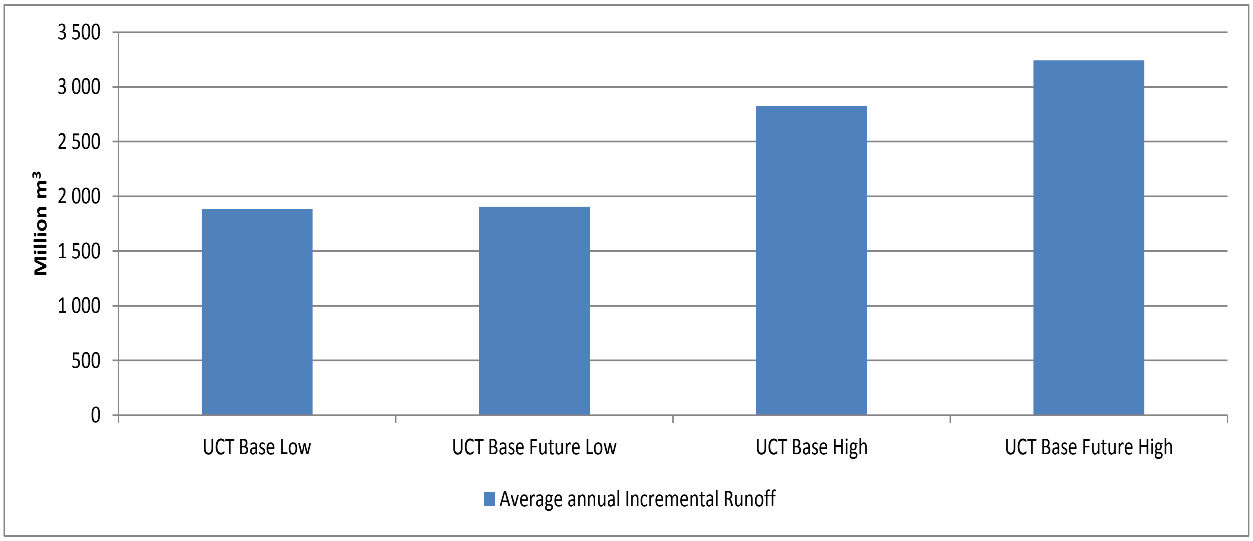


Figure 7: Average annual incremental runoff

Figure 8 presents the area under different irrigation intensities for the base scenarios. It is clear that there are not significant differences. However, the general trend is that in the "wetter" scenarios there is a larger area under optimal irrigation compared to the "dryer" scenario's (UCT Base Low and UCT Base Future Low). The results also indicate that there is mainly a substitution from supplemental irrigation to optimal irrigation.

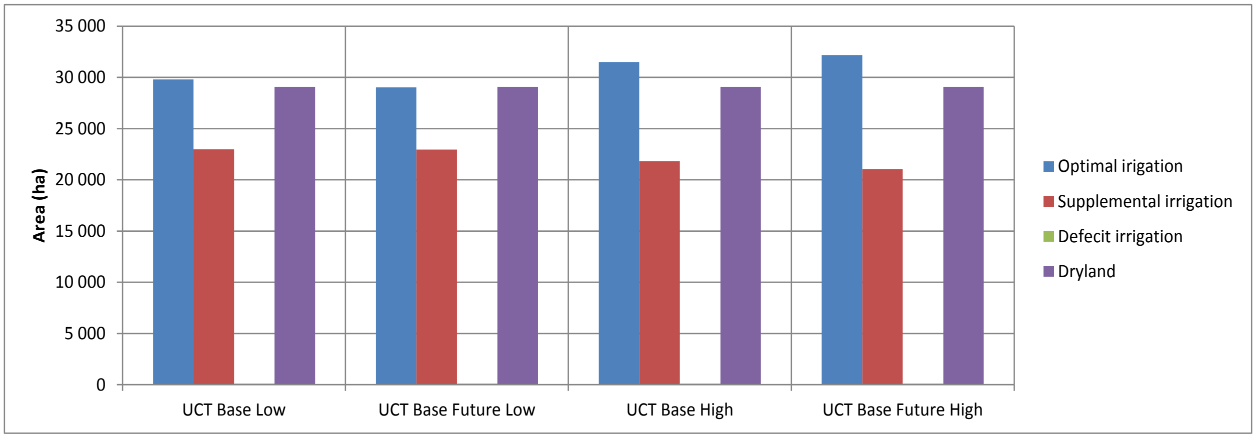


Figure 8: Base comparison – irrigation intensities

Figure 9 shows the change in crop combinations for the base scenarios. The key trend is that in the "dryer" base scenarios (UCT Low), there is a larger area under other crops (which is mainly dry land) and a smaller area under high value crops such as fruit. In the "wetter" scenarios, there is a slight decrease in the "other" crops and an increase in the area of fruit (mainly deciduous fruit). One of the shortcomings of the model is that crop-water and crop- temperature relationships were not modeled in detail since the model became too large to accommodate the level of detail which is required to adequately simulate these relationships. The authors are of the opinion that the farm models will become much more sensitive to climate change if these relationships are refined in future development of the model.

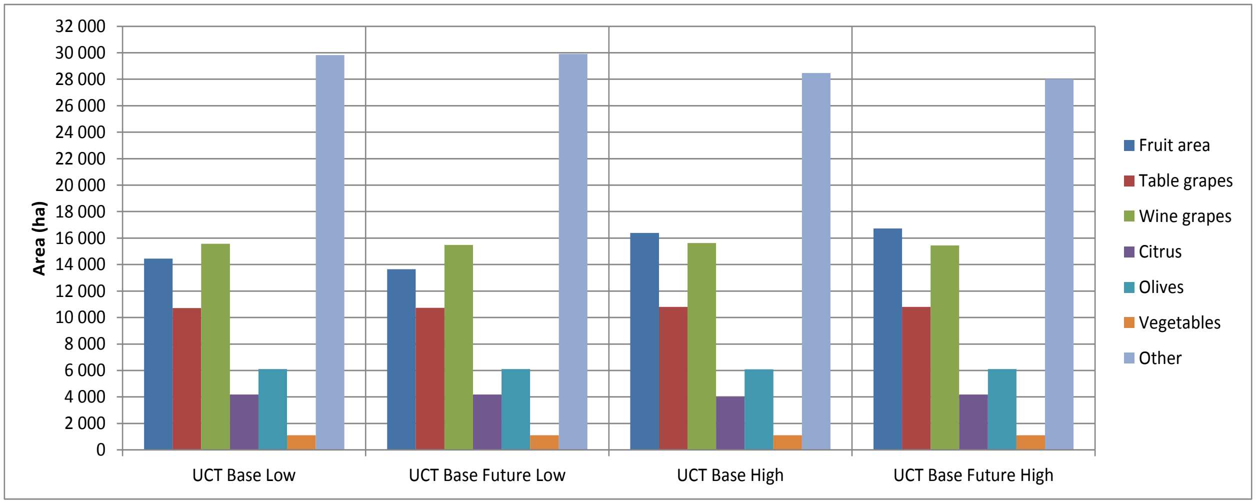


Figure 9: Base comparison - crop combination

The total average agricultural water use responds to the availability of water over the 20-year planning horizon. It is therefore obvious that if there is more water available, agriculture will respond by irrigating at more optimal irrigation intensities (and more profitable) which will result in an overall increase in the demand for water (see Figure 10). In the UCT Base High future scenario (wet), there is an increase in the average annual water use of almost 20 million m^3 compared to UCT Base High. and almost 80 million m3 compared to the UCT Base Low.

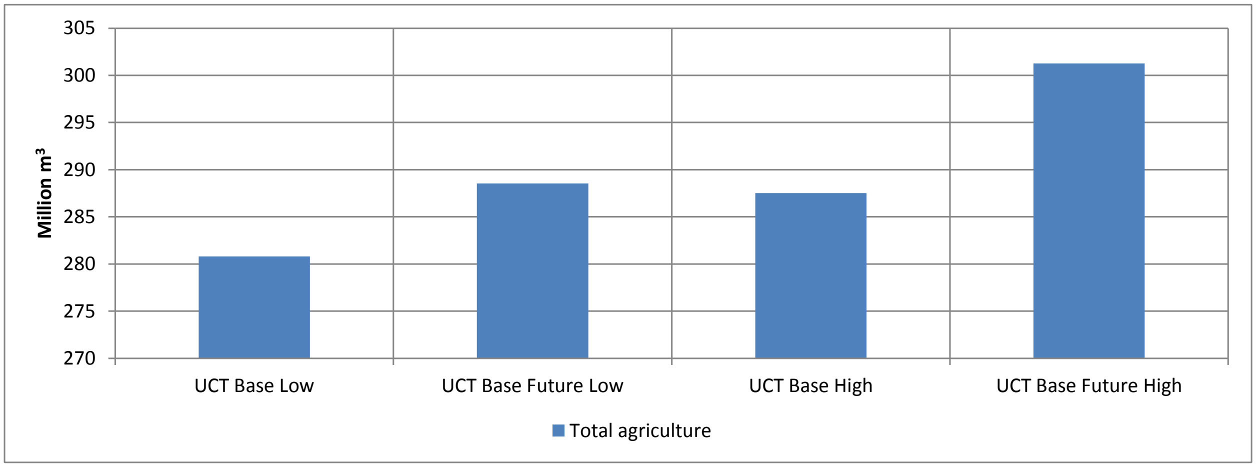


Figure 10: Total average agricultural water use per annum

The average annual urban water demand also responds to the availability of water since the value of the water is based on the scarcity value of the water. Since water is in general more scarce in the UCT Low water scenarios, the urban water demand is in general significantly lower compared to the “wetter” scenarios since urban users will respond to the higher value of the water by using less water (see Figure 11).

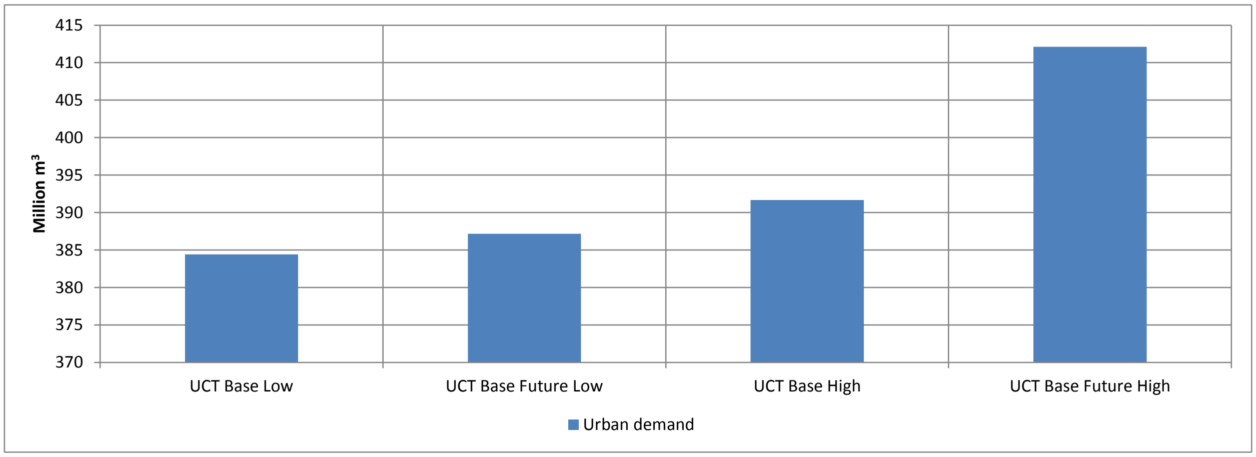


Figure 11: Average annual urban water demand

Runoff will have a significant impact on the storage level of the main dams. Figure 12 shows the average aggregated water storage for all the main dams in a particular month. It is clear that with the UCT Low scenarios the average monthly storage is significantly lower compared to the UCT High. The UCT Base Low Future scenario also indicates that the major dam water storage levels will be lower compared to the UCT Base Low with the exception of the month of May where a slightly higher average storage level is indicated.

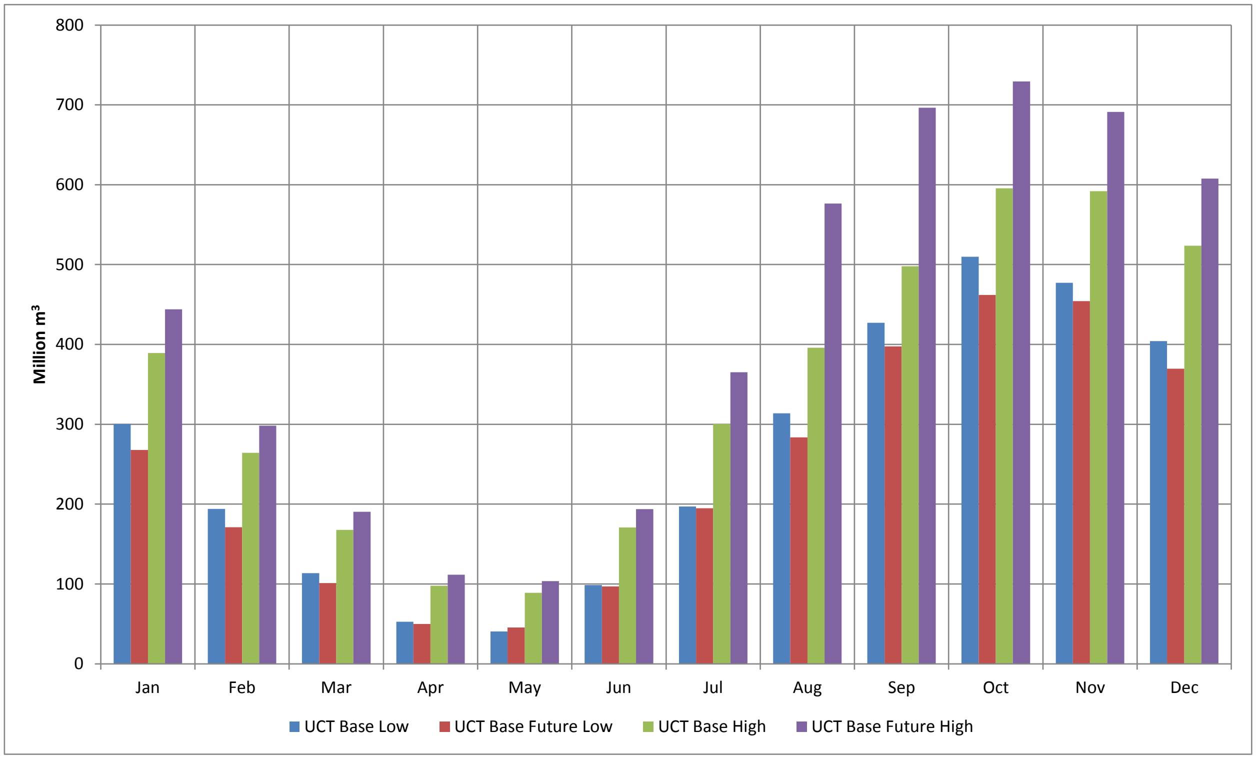


Figure12: Average monthly main dam storage

Figure 13 shows the total income from urban water sales as well as the total cost to deliver the water. It is clear that there is a direct correlation between the income and costs. When the income is higher it signifies an increase in water demand which is accompanied by an increase of delivery costs.

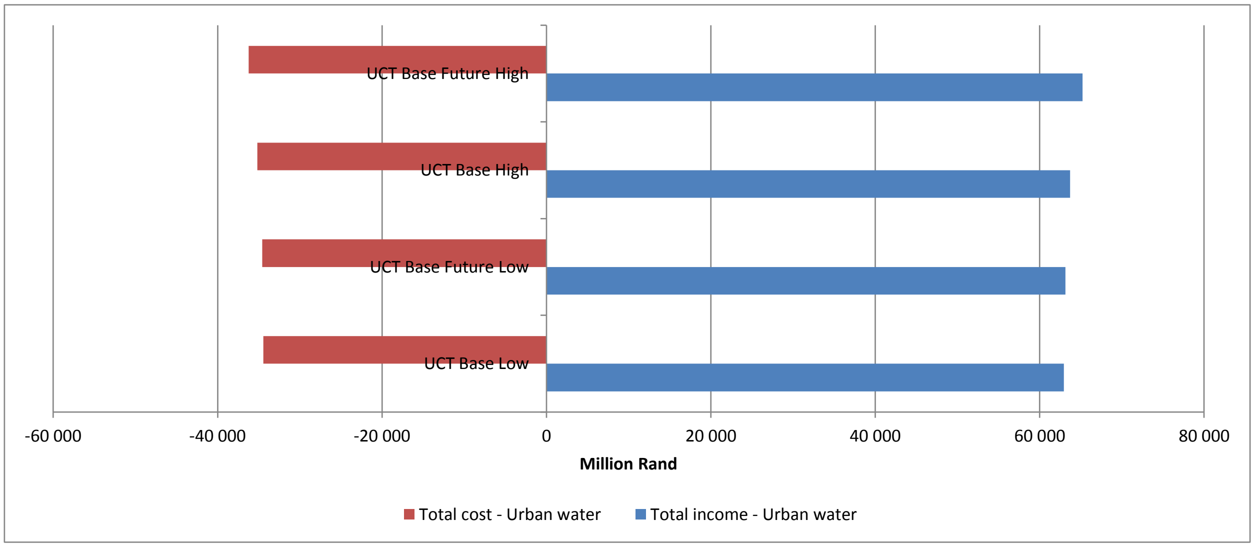


Figure 13: Total income and costs for the urban water sector

Similar to the urban water costs, the cost of water to the agricultural sector is also determined by the scarcity value, especially the value of water in farm dams since they are directly linked to the storage levels in the farm dams. If the farm dams do not fill up due to reduced runoff, the unit cost of farm dam water increases significantly due to the high fixed cost of the infrastructure. Figure 14 shows that for the UCT Low scenario, the total cost of agricultural water is significantly higher compared to the other base scenarios which are in general the "wetter" scenarios where the farm dams are more likely to fill up. It is also clear that there is not a significant difference between the total agricultural water cost in the UCT Base High and the UCT Base Future High since even when more water is used it is at a lower water unit cost (since more water is available).

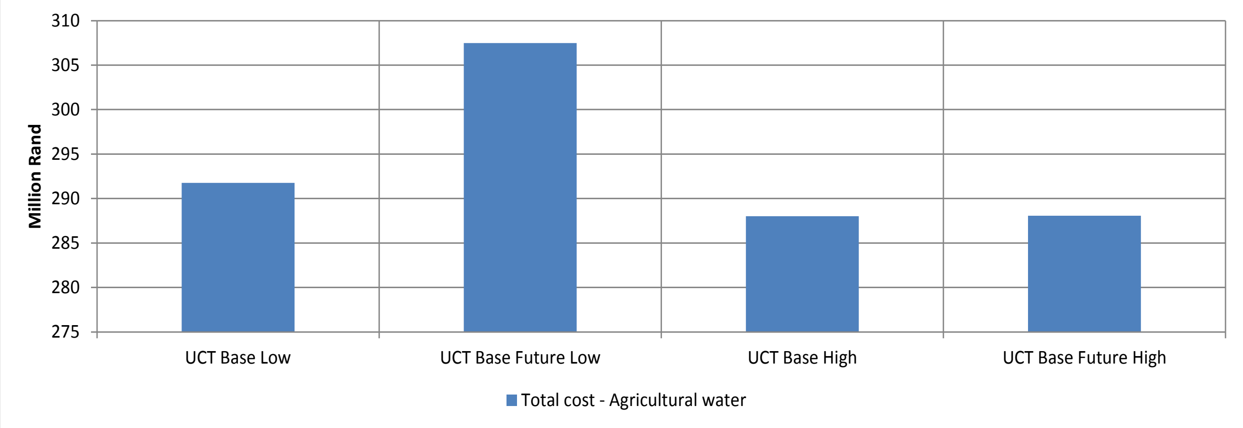


Figure 14: Total cost of agricultural water

Although not the only explanation, there seems to be a direct link between the total cost of agricultural water and the total Net Disposable Income for agriculture. However, the fact that higher value crops are produced when in the "wetter" scenarios also contributes to a higher Net Disposable Farm income for these scenarios (see Figure 15). In the UCT Base Future Low scenario the total Net Disposable Farm Income decreases with about R540 million. It is interesting to note that in the UCT Base Future High scenario ("wetter") there is also an increase of about R140 million in Net Disposable Farm Income over 20-years. This can be explained by a slight increase in the area under fruit production (high value) and an increase in more optimal irrigation technology.

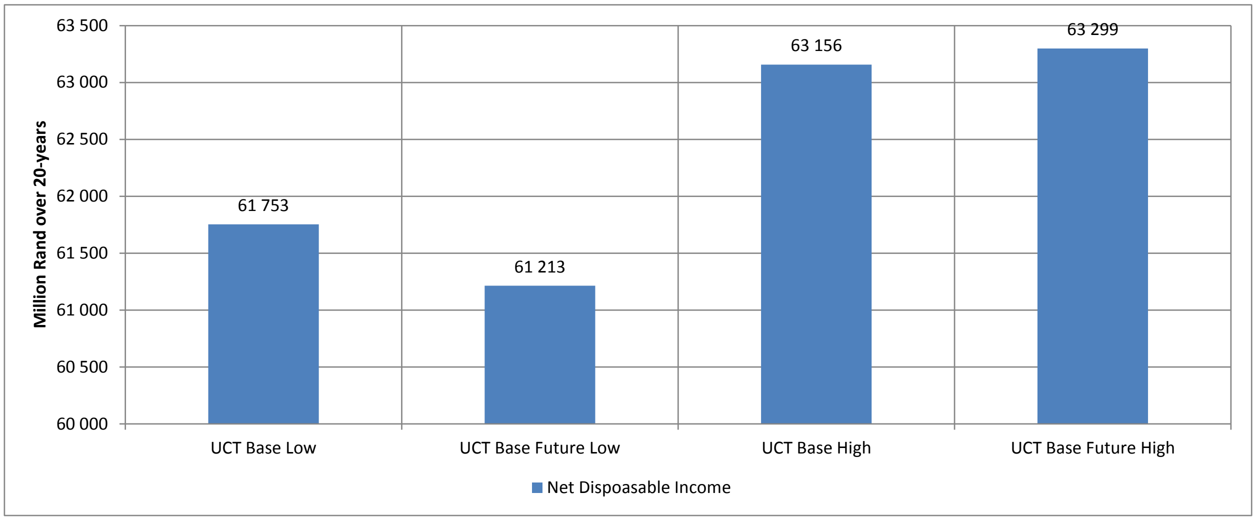


Figure 15: Net Disposable Farm Income – total over 20-years

Figure 16 shows the total welfare (or objective function value) for all sectors. In general, the "dry" climate scenarios (UCT Base Low and UCT Base Future Low) results in a lower overall welfare compared to the "wetter" scenarios where more water is available and where agriculture can produce higher value crops (both through more optimal irrigation and a change in crop structure) and where there is more water available for the urban sector. The results indicate that without any adaptation the total welfare in the UCT Base Future Low scenario will decrease with about R700 million. In the UCT Base Future High scenario the total welfare will increase with approximately R200 million mainly because of increasing water consumption by the Urban water sector and an increase in output in the agricultural sector.

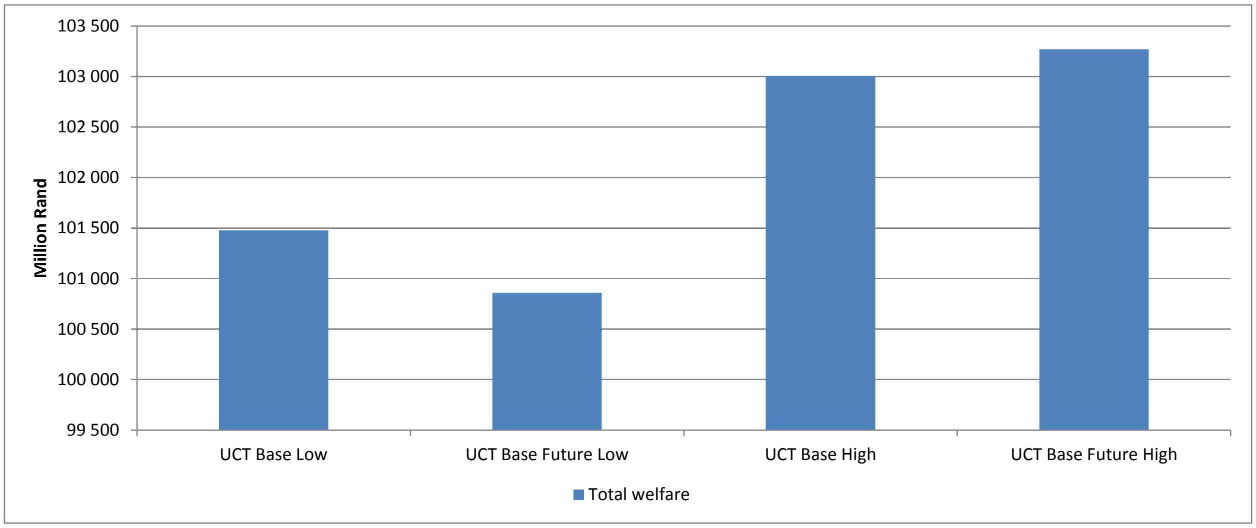


Figure 16: Total welfare – objective function value

The average capitalised marginal value of water gives an indication of the scarcity value of the water. In the UCT Base Low and the UCT Base Future Low scenarios the marginal value reflects that water is scarcer compared to the UCT Base High, the UCT Base Future High and the IRI scenarios (see Figure 17).

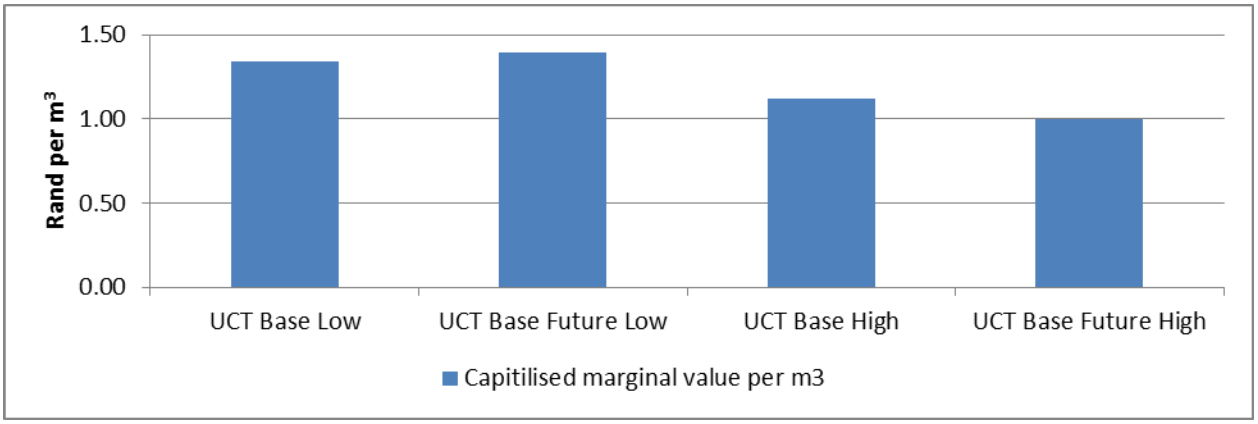


Figure 17: Average capitalised marginal value of agricultural water

The analyses which were described in this section give a clear indication that the integrated modelling framework can be used to simulate various climate change scenarios and that the results correspond with what can be expected from the impact on runoff, the farming systems, and urban water use.

6.2 APPLICATION TO EVALUATE AN INCREASE OF 20% IN FARM DAM CAPACITY AS ADAPTATION STRATEGY

The objective of the research was also to demonstrate how adaptation scenarios can be evaluated on their costs and benefits and the impact that they will have on dam storage levels, on agricultural and urban water use and on the value of water. For this purpose several scenarios were analysed where the farm dam capacity was increased by 10%, 20% and 30%. However, for the purpose of this paper only the results of a 20% increase in farm dam capacity are reported. The analysis compares the relative change between the UCT Low Base and The UCT Low Distant Future and between the UCT High Base and the UCT High Distant Future.

Figure 18 shows the relative change in the area under different irrigation intensities when there is a 20% increase in farm dam storage capacity. In the UCT High Distant scenario (wetter), the area under deficit and supplemental irrigation decreases and the area under optimal irrigation increases since there is more water available and irrigation scheduling / management can improve with an increase in farm dam capacity. In the UCT Low Distant scenario, the area under optimal irrigation and deficit irrigation decreases and there is an increase in supplemental irrigation even if there is a 20% increase in farm dam capacity.

The explanation for this is that in the UCT Low Distant scenario the farm dams, not even the existing farm dams, do not fill up. Adding more farm dam capacity in this scenario only contributes to even higher agricultural water costs since the cost per unit of water stored in farm dams increases significantly. However, it is clear that when farm dam capacity is increased in the UCT High Distant scenario the farm dams will fill up and this results in a change towards more optimal irrigation.

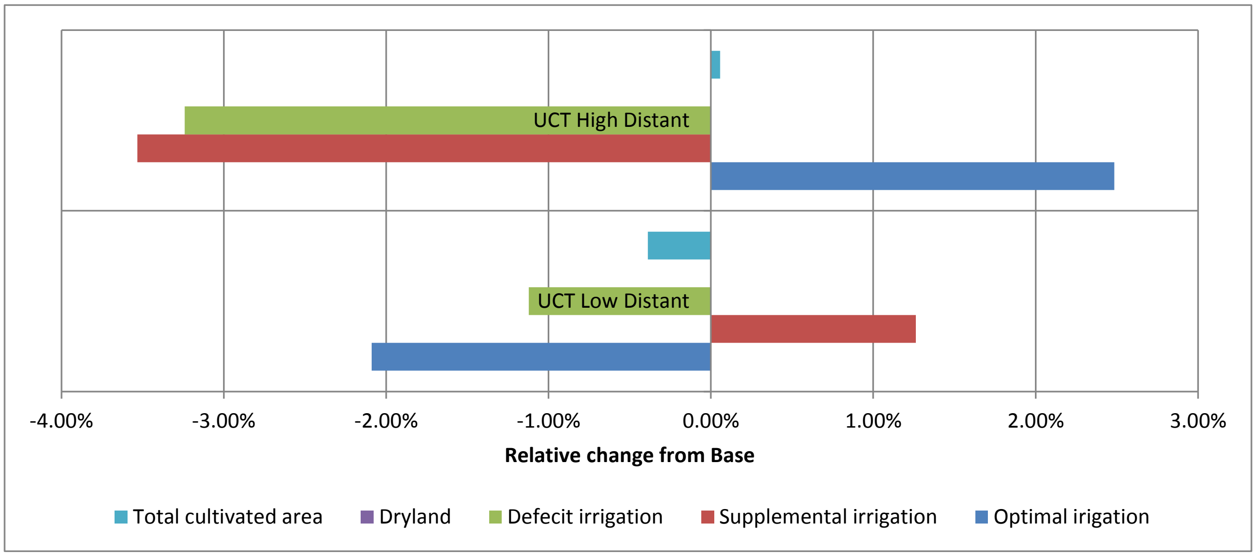


Figure 18: Irrigation intensity

The UCT Low Distant scenario results in a reduction in the area under fruit production (most of the fruit must be irrigated optimally for the fruit export market). The UCT High Distant Future indicates that increasing farm dam capacities by 20% will have a positive impact on fruit production in the region since more water will be available for optimal irrigation. It is also significant to note that in the UCT High Distant scenario there is a significant increase in Citrus production. Although not shown in this report, the runoff in the Piketberg / 24-Rivieren region (main Citrus region in the study area) actually increases, which results in more water storage in farm dams and therefore a potential to increase citrus production.

Increasing farm dam capacities in the UCT Low Distant Future scenario also result in an increase in table grape production and other short-term irrigation crops which can be irrigated with supplemental irrigation.

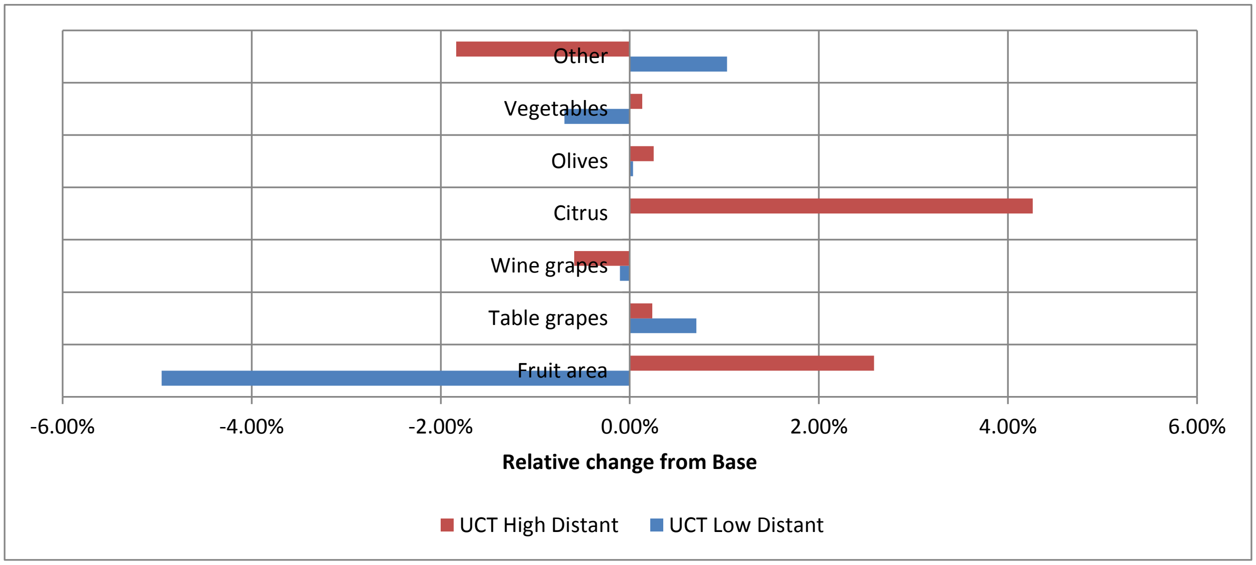


Figure 19: Crop combinations

Figure 20 shows the relative impact of an increase in farm dam capacity on the total agricultural water use. The model indicates that the total agricultural water use in the low distant scenario increases slightly but not to the same extent as the UCT High Distant scenario since the farm dam storage levels are lower. However, the model indicates that the water use per ha irrigated in the UCT Low Distant scenario significantly increases mainly because of structural changes and higher temperatures which results in an increase in the crop water use requirements.

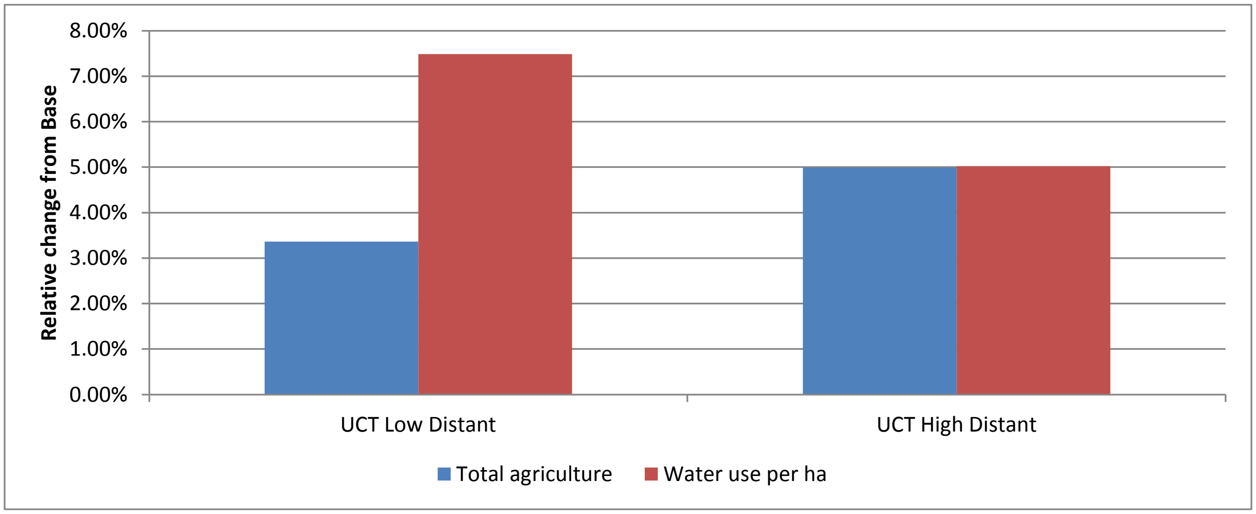


Figure 20: Agricultural water use

With the exception of the UCT High Distant scenario (significant increase in runoff), the model indicates that increases in farm dam capacities will not result in significant changes in the urban water demand (see Figure 21). The increased demand in the UCT High Distant scenario can be explained by the higher on-farm storage capacity and availability of farm dam water and therefore a reduced dependence on the main storage dams and therefore a higher availability of water supplies to the urban water use sector.

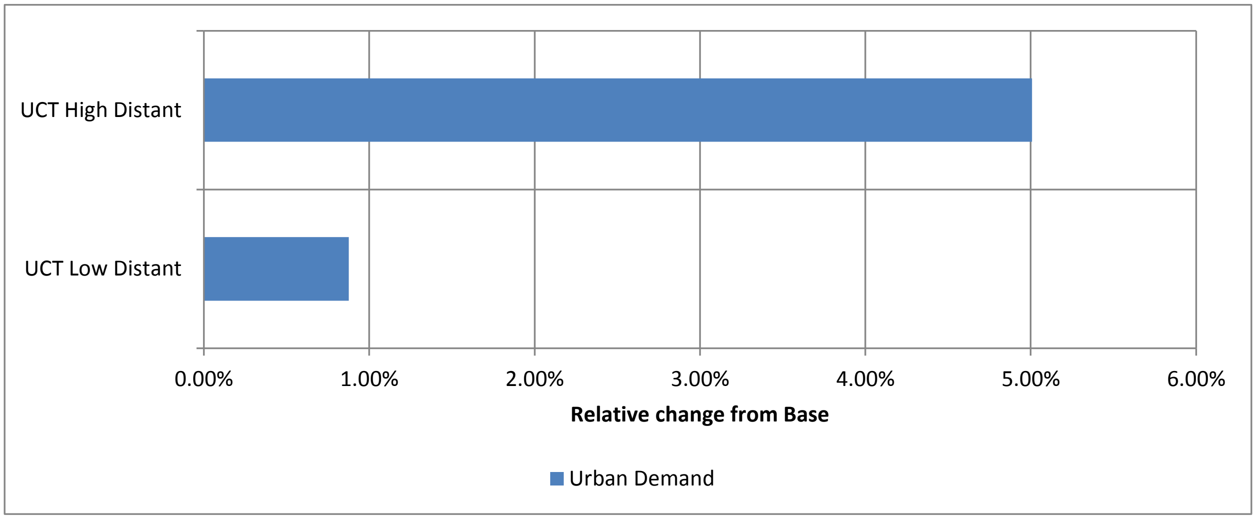


Figure 21: Urban water demand

The average monthly urban water demand is shown in Figure 22. It is clear that the monthly urban water demand for the UCT High Distant scenario will increase significantly with an increase in farm dam capacity. Although not significant, the UCT Low Distant Future also indicates that increasing farm dam capacities will result in more water available for the urban sector.

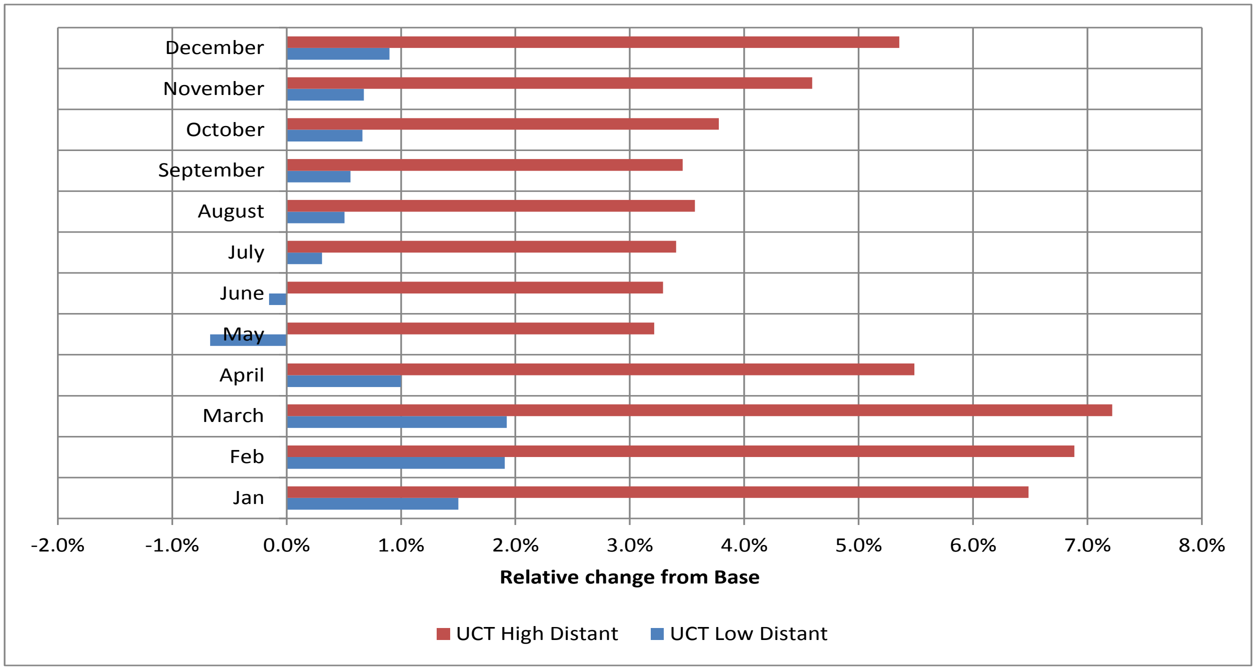


Figure 22: Average monthly urban demand

Figure 23 indicates that the average storage level for the major dams will increase in the "wetter" scenario ("high") when there is an increase in farm dam capacities since it will result in a reduced dependence on water to be released from the main dam storage for irrigation purposes.

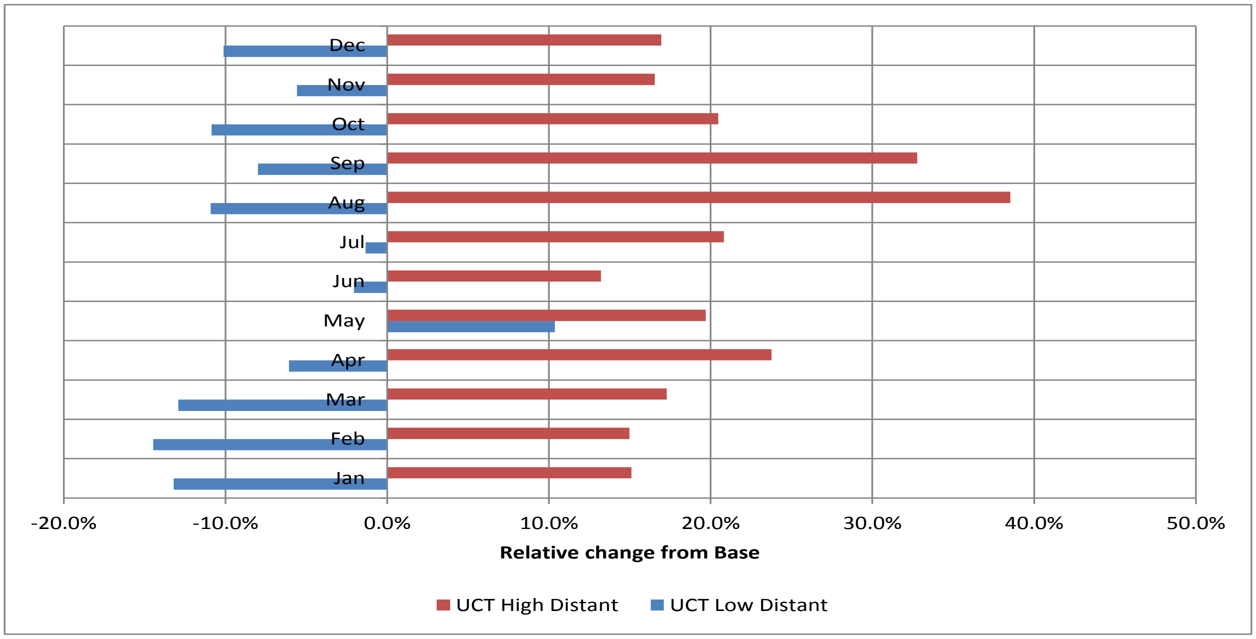


Figure 23: Average monthly main dam storage

However, the results for the UCT Low Distant Future scenarios indicate that increasing farm dam capacities will not result in a positive impact on main dam storage levels for most months. This impact can be explained by the farm dams that don't fill up even with an increase in storage capacity and an increased dependency on irrigation from main storage dams.

It was pointed out earlier in that there is a direct correlation between the income derived from water sales to the urban sector and the water supply cost. However, the water supply cost is also determined by the scarcity value of the water. In the "dryer" scenarios the scarcity value is high which results in an increase in the water supply cost to the urban sector. It is clear from Figure 24 that the water supply cost relative increase is higher compared to the relative increase in income from water sales to the urban sector. However, the explanation for this is not the same in both scenarios. In the UCT High Distant Scenario there is a significant increase in both the Urban and Agricultural water demand which results in a relative scarcity even if there is more water available.

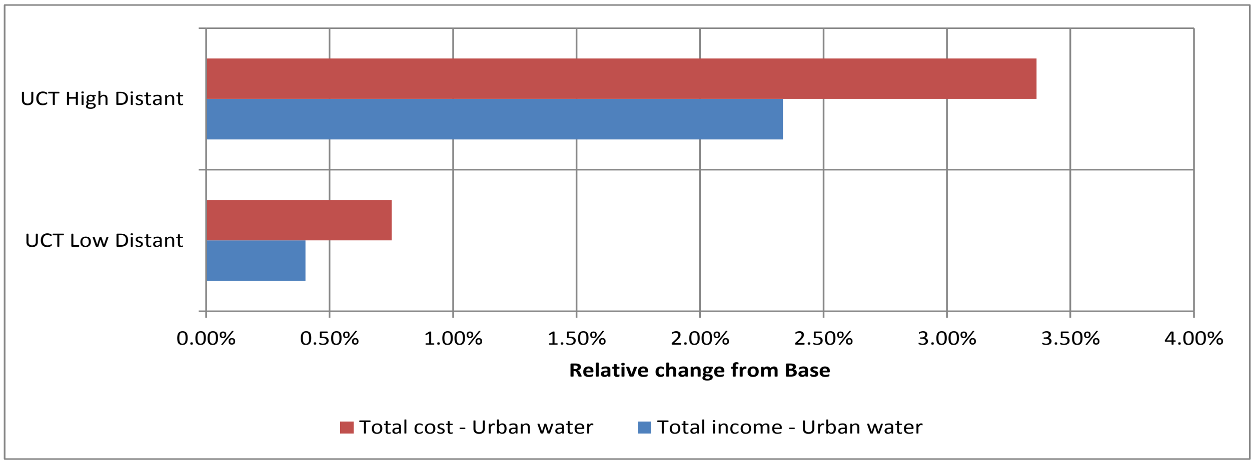


Figure 24: Total urban water costs and income from urban water sales

Figure 25 shows the relative change in the total cost of agricultural water with an increase in farm dam capacities. It is significant to note that the highest relative change is for the UCT Low Distant scenario due to the high unit cost for farm dam water if they don't fill up their capacity frequently.

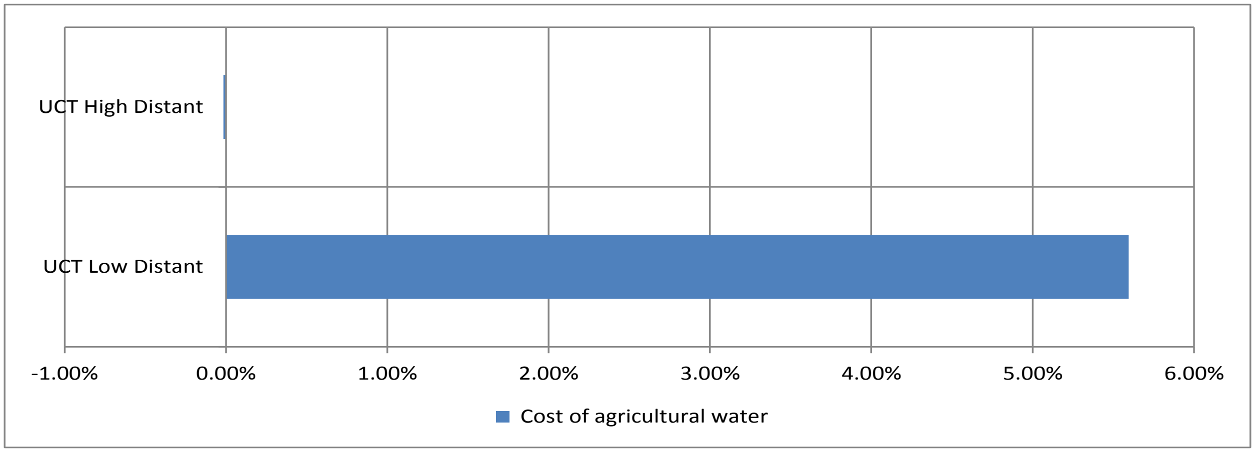


Figure 25: Costs of agricultural water

The results for the UCT High Distant scenario show that increasing farm dams will not result in higher agricultural costs since the farm dams will frequently fill up resulting in a lower unit cost for farm dam water.

Although there are not significant relative changes in the overall Net Disposable Farm Income, the UCT Low Distant and the UCT High Distant scenarios indicate a slightly negative impact on Net Disposable Farm Income. The negative impact can be explained by the higher water cost (see Figure 26).

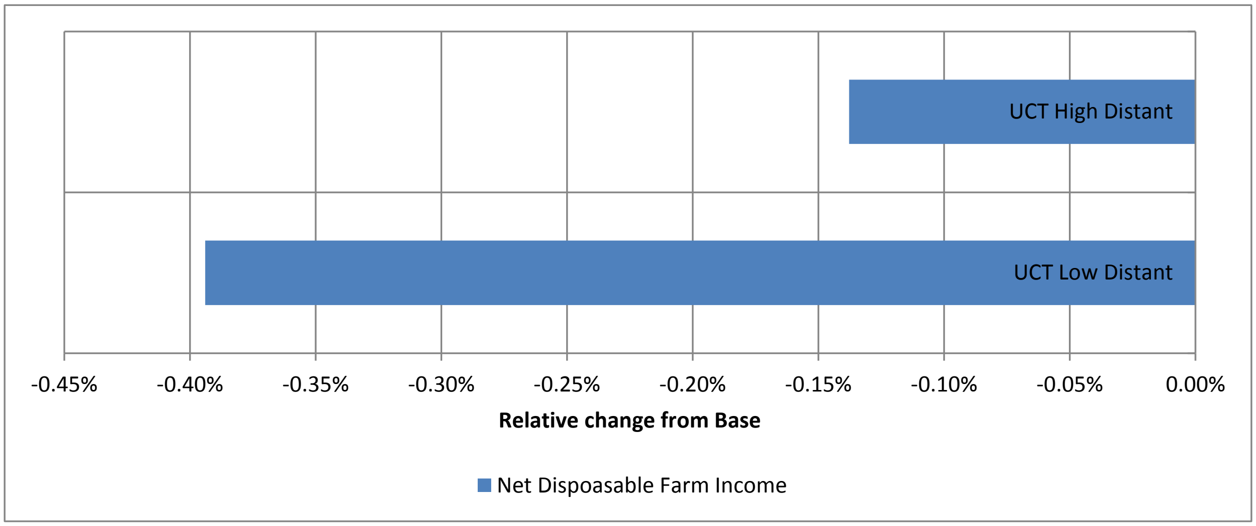


Figure 26: Net Disposable Farm Income over 20-years

Figure 27 shows the relative change in total welfare due to an increase in farm dam capacity. These results show why it is so important for an integrated and multi-sectoral approach in the evaluation of adaptation strategies. The results indicate that with the UCT Low Distant scenario increasing farm dam capacity as an adaptation strategy will not be beneficial. However, an increase in farm dam capacity will be beneficial in the “wet” scenario since both the agricultural and the urban sector will benefit.

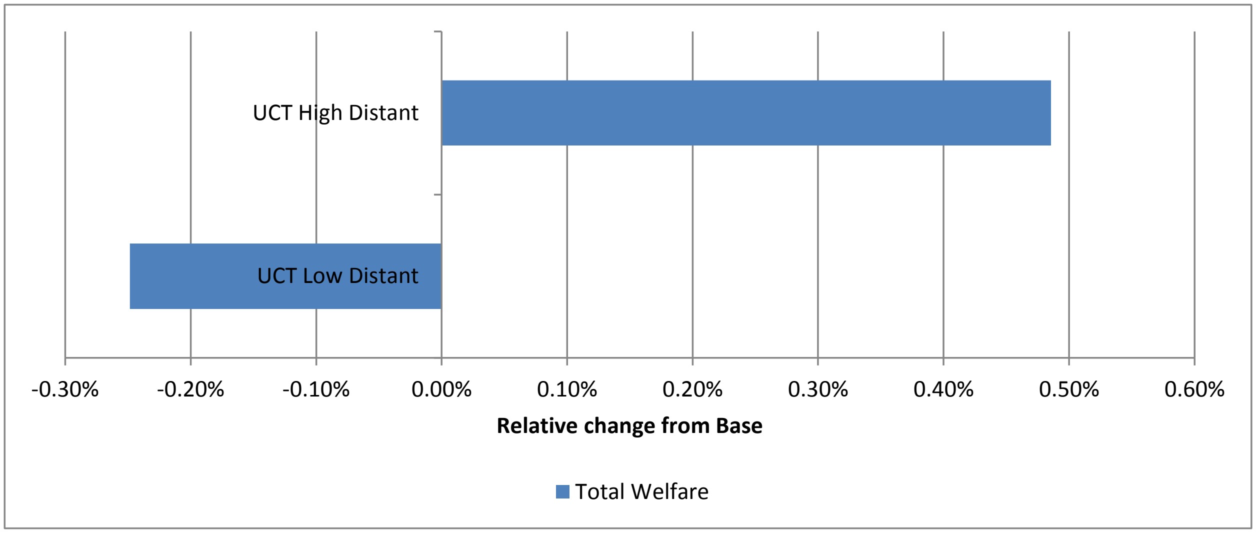


Figure 27: Total welfare – objective function value

The relative change in the average capitalised marginal values for agricultural water is shown in Figure 28. Figure 29 shows the relative change in incremental runoff for each of the scenarios. It is clear that there is a strong correlation between the scarcity (in this case derived from runoff) value and the total runoff. In the UCT Low Distant scenario, the marginal values slightly increase even with a slight increase in the average annual runoff (although insignificant). The result indicates that building farm dams that don’t fill up may even contribute to water scarcity?

For all the other scenarios the marginal values correspond directly with the relative change in runoff.

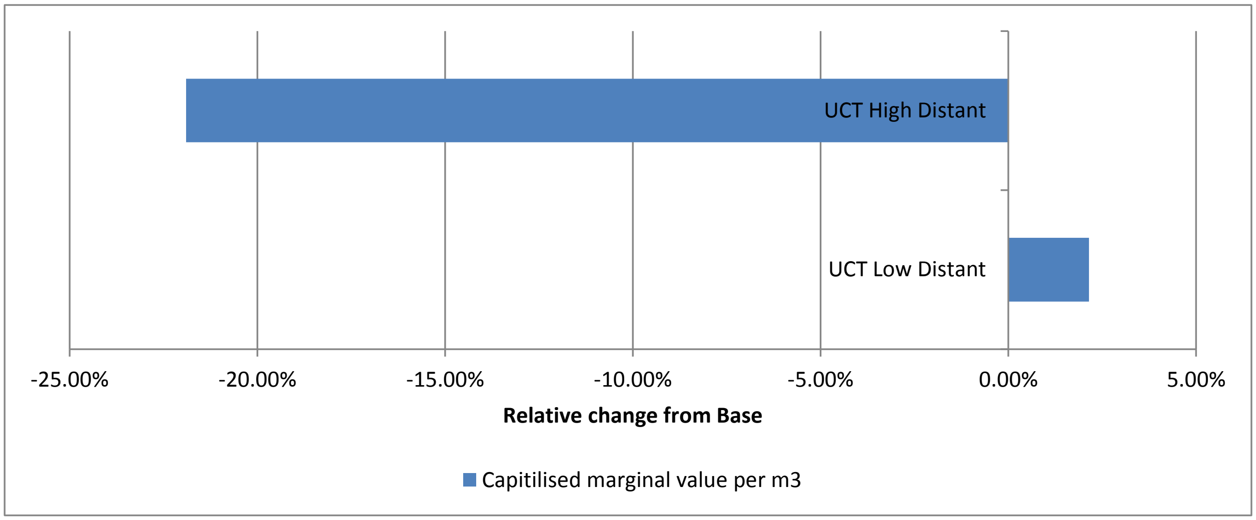


Figure 28: Capitalised marginal value of agricultural water

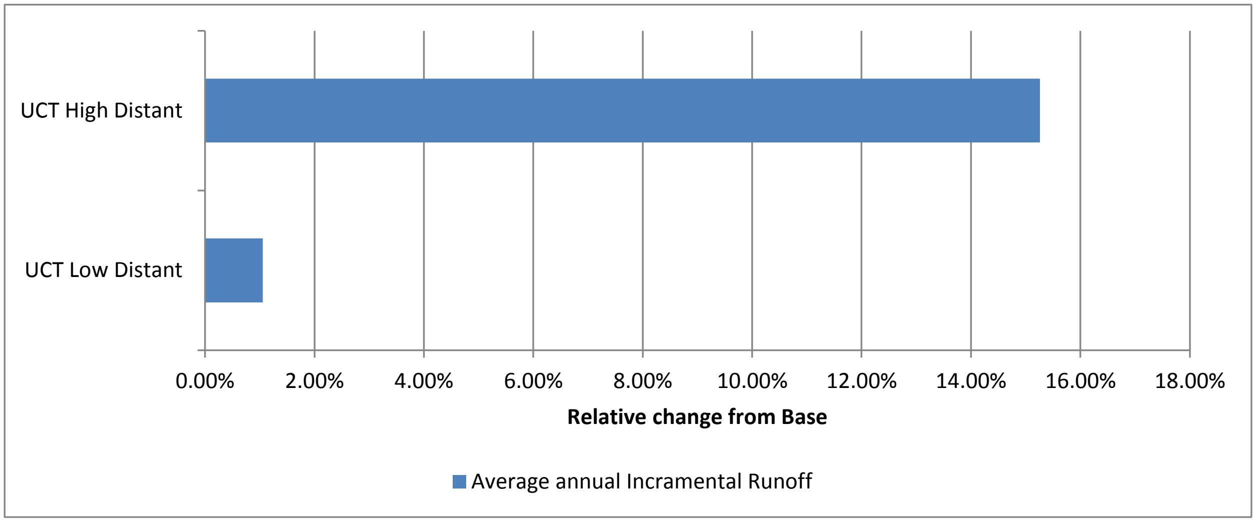


Figure 29: Average annual incremental runoff

7. CONCLUSION

Responding to climate change impacts through appropriate adaptation and mitigation mechanisms requires practical resilient solutions in the form of **technological, social and economic aspects.** These can be developed through systematic research on climate change and associated impacts. In many African countries there is limited research on climate change and related impacts on livelihood, natural resources. This is partly attributed to limited funding for research on climate change impacts, adaptation and mitigation; limited focus and prioritisation by researchers to study climate change; inadequate facilities for collection of weather information on climate change by region. Overall this has an implication of limited knowledge and information on appropriate options to support climate change adaptation and mitigation thereby increasing vulnerability to climate change impacts at all levels.

South Africa is blessed by the fact that there are researchers and adequate facilities to conduct research that will improve the knowledge on how the technical, social and economic elements of climate change can be integrated to provide a holistic solution to adaptation to climate change. The objective of the modelling exercise was to demonstrate that it is possible to develop an integrated modelling framework for evaluating and making adaptation decisions related to water resources in the Western Cape. It should be possible to duplicate the integrated framework elsewhere in Africa.

The results of the Set 1 analysis (comparison of the Base analysis of different climate change scenarios) which was described in this paper gives a clear indication that the integrated modelling framework can be used to simulate various climate change scenarios and that the results correspond with what can be expected from the impact on runoff, the farming systems, and urban water use.

The Set 2 analysis clearly illustrated that the development of 20% additional farm dam capacities is not a good adaptation strategy for the Low flow scenarios. If the farm dams don't fill up, it may even worsen the situation of farmers since the high capital cost and resulting high unit cost of farm dam water will increase their financial vulnerability. A more effective adaptation strategy in the Low flow scenario would probably be to increase overall irrigation efficiency and to make structural changes (increase the ratio of short-term to long-term crops).

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