THE IMPACT OF CLIMATE CHANGE ON HYDROLOGICAL PREDICTIONS, WITH SPECIFIC REFERENCE TO 24-HOUR RAINFALL INTENSITIES IN THE WESTERN CAPE

by

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Mr JA du Plessis
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Declaration

I, the undersigned, hereby declare that the work contained in this thesis is my own original work and that I have not previously in its entirety or in part submitted it at any university for a degree.

Signature:…………………………..

Date:………………………………..

Abstract

The climate of the world varies from one decade to another, and a changing climate is natural and expected. However, there is a well-founded concern that the unprecedented human industrial development activities of the past two centuries (and mainly the last century) have caused changes over and above natural variation. Climate change is the natural cycle through which the earth and its atmosphere are going to accommodate the change in the amount of energy received from the sun.

There are various indicators that can be monitored to measure and verify possible climatic changes. This thesis will firstly emphasize what the possible effects of climate change could be on amongst others, the coastal zone, biodiversity and water resources. If the impact of climate change on the above mentioned processes are monitored, and changing trends can be identified, these processes could in fact be seen as climate change indicators. This is of major importance to us, to be able to accurately identify whether climatic changes are experienced in any given area and to attempt to quantify it.

Engineering hydrologists are, amongst other duties, responsible for the determination of peak discharges to be able to size conduits to safely convey the stormwater for given recurrence interval events. All hydrological predictions are indirectly or directly based on historical data. Empirical formulas and deterministic methods were developed and calibrated from known historical data. Statistical predictions are directly based on actual data. The question that arises is whether the historical data still provides an accurate basis from which possible future events can be predicted?

This thesis strives to find an answer to this question and will also try to advise hydrologists on how they should interpret historical data in the future, taking climate change into consideration. The methodology that will be followed will be to compare the percentage of occurrence of 24-hour rainfall events of different magnitudes, for historical- as well as predicted rainfall, for five different rainfall stations in the Western Cape. A detailed analysis of measured data at a rainfall station, with 42 years of useable data, will also be performed, to verify whether any measurable trends have already been experienced. Conclusions shall be drawn as to possible trends, and recommendations will be made as to how hydrologists could allow for the possible changing rainfall patterns.

Opsomming

Die klimaat van die wêreld verander van dekade tot dekade, en 'n veranderende klimaat is natuurlik en te verwage. Daar is egter 'n bekommernis dat die ongekende industriële ontwikkelings aktiwiteite van die laaste twee eeue, veranderinge bo die normale variasie tot gevolge het. Klimaats-verandering is die natuurlike kringloop waardeur die aarde en die atmosfeer gaan, om te akkommodeer vir die veranderde hoeveelheid energie wat vanaf die son ontvang word.

Daar is verskeie aanwysers wat gemonitor kan word om moontlike klimaats-veranderinge te bevestig. Hierdie tesis sal van die moontlike gevolge wat klimaats-verandering op onder andere die kus-sone, bio-diversiteit en water-hulpbronne kan hê, uitlig. Indien die impak van klimaats-verandering op enige van die bogenoemde prosesses gemonitor kan word, en indien enige veranderende tendense ge-identifiseer kan word, kan so 'n proses as 'n klimaats-veranderings-aanwyser gesien word. Dit is van uiterste belang vir ons, om ons in staat te stel om te identifiseer of klimaats-veranderinge teenwoordig is in 'n gegewe area.

Ingenieurs hidroloë is, onder andere, verantwoordelik vir die bepaling van piek vloeie, om hulle in staat te stel om stormwater stelsels te ontwerp wat die gegewe ontwerp-herhaalperiode piekvloei, veilig sal kan akkomodeer. Alle hidrologiese berekeninge is direk of indirek op historiese data gebasseer. Empiriese formules en deterministiese metodes is afgelei van historiese data. Statistiese metodes is direk op historiese data gebasseer. Die vraag wat gevra word is of historiese data steeds van toepassing sal wees, indien klimaats-veranderinge plaasvind in 'n gegewe studie area.

Hierdie tesis sal daarna streef om bogenoemde vraag te beantwoord, en sal ook uitlig hoe hidroloë moontlik in die toekoms te werk sal moet gaan om klimaats-verandering in ag te neem. Die metodiek wat gevolg sal word is om die persentasie voorkoms van verskillende grootte 24-uur reënval storms vir historiese- sowel as voorspelde reënval te bepaal en vir vyf verskillende reënval stasies te vergelyk. 'n Detail studie sal ook gemaak word by 'n reënval stasie met 42 jaar se data, om te identifiseer of enige meetbare veranderinge in reënpatrone reeds waargeneem kan word. Gevolgetrekkings sal gemaak word oor moontlike tendense, en aanbevelings sal gemaak word oor hoe hidroloë voorsiening sal moet maak vir moontlike veranderde reënval patrone.

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1. Introduction

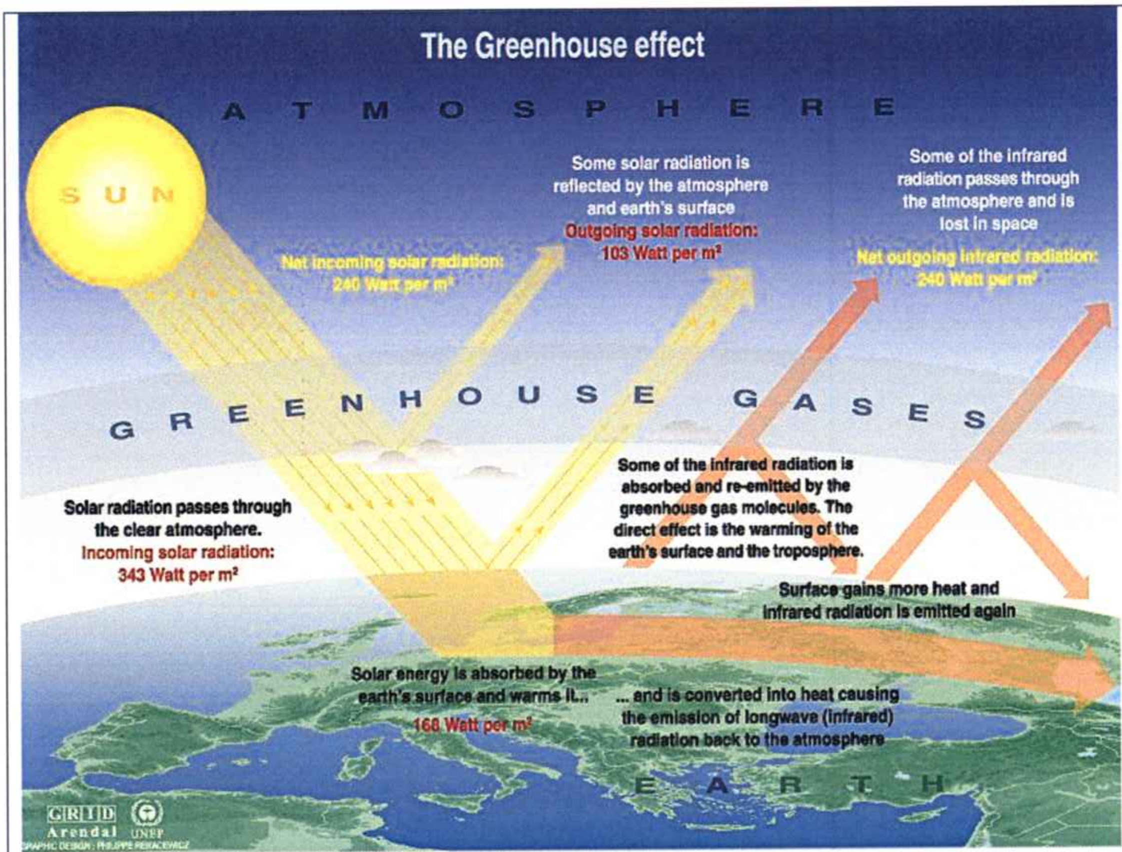
1.1 What is climate change and what processes drive it?

The climate of the world varies from one decade to another, and a changing climate is natural and expected. However, there is a well-founded concern that the unprecedented human industrial development activities of the past two centuries have caused changes over and above natural variation.

So what is climate change? Climate change is the natural cycle through which the earth and its atmosphere are going to accommodate the change in the amount of energy received from the sun (SA Weather bureau, 2005). The climate goes through warm and cold periods, taking hundreds of years to complete one cycle. Changes in temperature also influence the rainfall, but the biosphere is able to adapt to a changing climate if these changes take place over centuries. There is a concern that human intervention could currently cause the climate to change too fast. Plants and animals may not be able to adapt as quickly to this "rapid" climate change as humans can, and therefore the whole ecosystem could be in danger (SA Weather bureau, 2005).

The next important question is, what processes drive climate change? The global climate system is driven by energy from the sun. Several gases in the atmosphere act to trap the energy from the sun, thus warming the earth. These gases are called *greenhouse gases* and the process is the *greenhouse effect*. Without this, there would be no life on earth. Human activities over the last 200 years, particularly the burning of fossil fuels (oil, coal, natural gas) and the clearing of forests, have increased the concentration of greenhouse gases in the atmosphere. This is likely to lead to more solar radiation being trapped, which in turn will lead to the earth's surface warming up. This is called the *enhanced* greenhouse effect and is graphically illustrated in Figure 1.1 (Climate change information kit, 1999).

The South African National Biodiversity Institute, SANBI, expresses the following view: “Our lifespans represent a mere snapshot in time. While we mark the decades, Earth’s history is measured in thousands to millions of years. So we could be forgiven for thinking that climate change is something new. But it's all happened before. Over the last 500 000 years, the Earth has warmed and cooled at least 20 times, with glaciers retreating and advancing and sea levels rising and falling in response. Sometimes changes have been rapid and extreme, with mean temperatures fluctuating by more than 2°C in 50-100 years."



Sources: Okanagan university college in Canada, Department of geography, University of Oxford, school of geography; United States Environmental Protection Agency (EPA), Washington; Climate change 1995, The science of climate change, contribution of working group 1 to the second assessment report of the intergovernmental panel on climate change, UNEP and WMO, Cambridge university press, 1996.

Figure 1.1: The Greenhouse effect (Climate change information kit, 1999)

What is new, however, is that recently human activity could contribute to the Earth's climate change. Recent research shows that temperatures are rising higher and faster than can be explained by natural phenomena such as solar activity (National Biodiversity institute, 2005). Instead, rising temperatures mirror increases in the concentrations of "greenhouse gases." Gases like carbon dioxide and methane naturally trap heat in the atmosphere, making the Earth a pleasant place to live. But in the last 150 years, fossil fuels have powered the industrialized world, carbon dioxide levels have increased by more than 35%, and the consequent "greenhouse effect" could accelerate climate change.

So, is the climate really changing (National Biodiversity institute, 2005)?

- Temperature reconstructions since AD 1000 indicate that the 20th Century was unusually warm - and the 1990s was the hottest decade on record.
- Global sea levels rose 10-25 cm in the last century.
- Glaciers in the European Alps have lost half their volume since the 1850s.
- In the Antarctic, the five most northerly ice shelves retreated dramatically between 1945 and 1995, and the Arctic ice-cap has thinned by 40% since the 1950s.

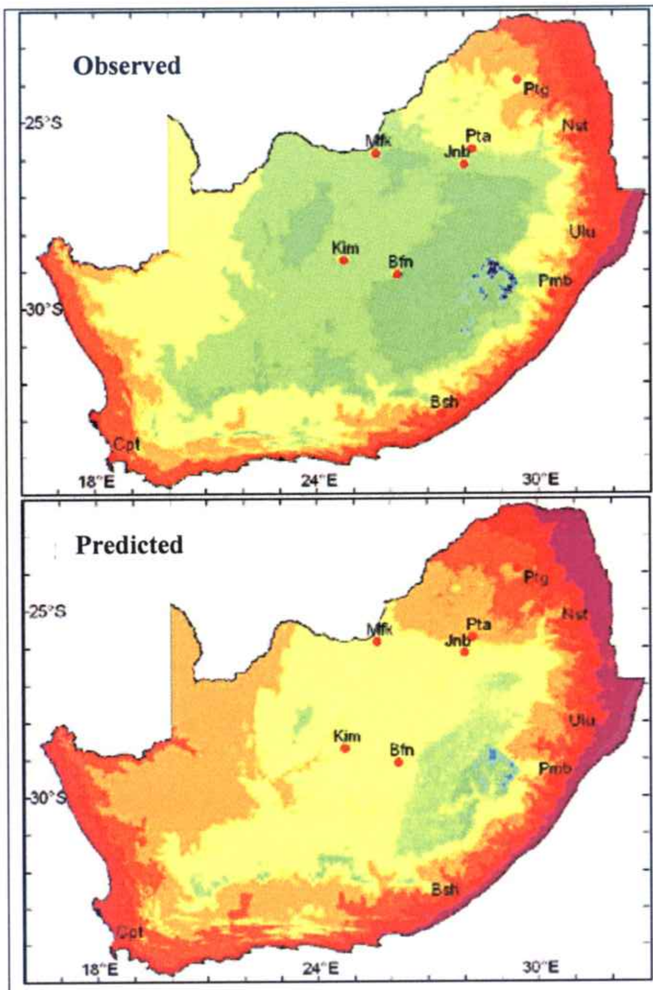
In view of the above facts, we cannot deny the fact that the climate is changing rapidly.

Climate change research is both complex and uncertain. This is because climate itself is the result of complex interactions between the Earth's atmosphere, oceans and land surfaces, that we do not fully understand. In order to simulate and predict climate, scientists have developed computer programs known as General Circulation Models or GCMs. If, for example, information about the concentration of greenhouse gases in the atmosphere is given, these models can roughly predict the climatic conditions that will result. The "*South African Country Study*" was based on climate predictions for the year 2050 produced by two internationally renowned institutes, the Hadley Centre (UK) and National Centre for Atmospheric Research (NCAR, USA). These predictions assume an increase in atmospheric carbon dioxide (CO_2) from about 370 ppm in the year 2000 to 550 ppm in 2050 (National Biodiversity institute, 2005).

Results from the above-mentioned computer models predict that climate will probably not change uniformly across the globe. Land areas will warm up faster than the oceans and polar latitudes faster than temperate latitudes. Coastal temperatures will generally rise slower than inland, thanks to the moderating effect of the ocean. In the Northern Hemisphere, global warming may actually benefit agriculture, as areas that are currently too cold to farm, becomes warmer. On the other hand, agriculture faces an uncertain future in the Southern Hemisphere, where large areas will become as much as 3°C warmer and much drier. Higher temperatures are predicted over most of South Africa. January temperatures are expected to increase most in the central interior and Northern Cape (2.5-4.5°C), and least at the coast (0.5-1.0°C). In general, summer rainfall will decrease by between 5% in the northern regions and 25% in the

Eastern and southern Cape. The Western Cape may lose as much as 25% of its current winter rainfall.

The following three figures graphically illustrate some of the predictions obtained from the above-mentioned models.



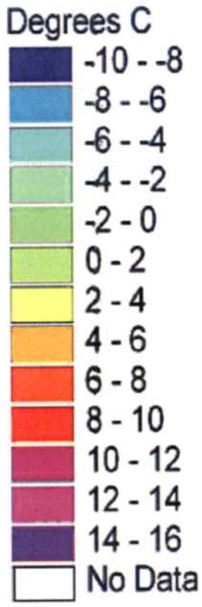


Figure 1.2a: The predicted effect of global climate change on ***minimum temperatures*** in July in South Africa, according to The National Biodiversity Institute of South Africa

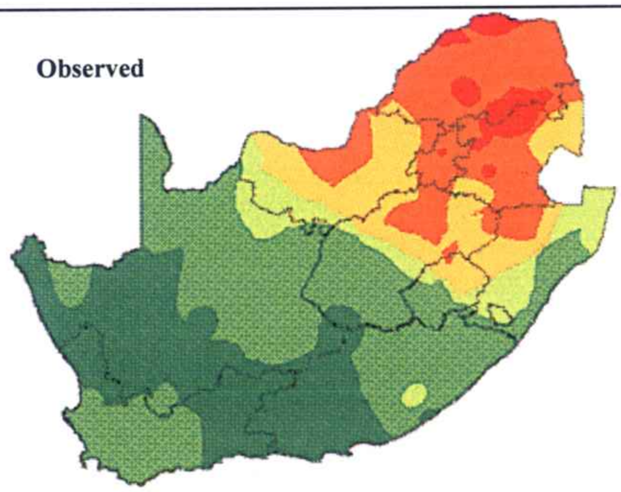
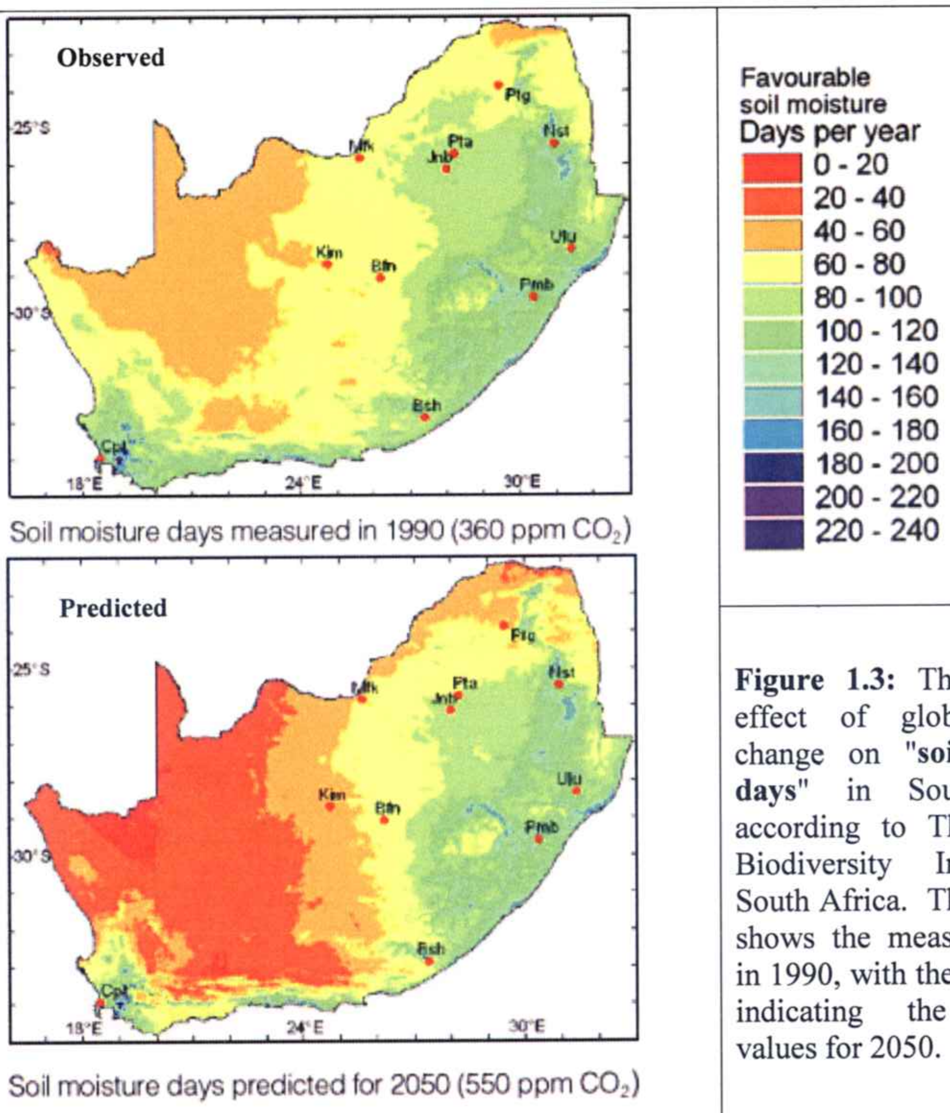


Figure 1.2b: Observed average temperature deviations from normal (in degrees Celcius) measured during the first 10 days of June 2005 according to The South African Weather service – (Green indicate cooler than normal temperatures, and red indicate warmer than normal temperatures. Despite the very short period, a trend underlining the predictions, can already be seen from the measurements).

It is clear that the northern parts of the country and some of the central regions experienced temperatures warmer than what are usual for the first ten days of June. The rest of the country experienced temperatures within the normal range, with the exception of a region lying in a Northwest to Southeast band across the country that experienced below normal temperatures for this ten-day period. Figure 1.2b indicates that temperature changes are already occurring. It must be stated however that these cannot implicitly be coupled to climate change.

Figure 1.3, illustrates the influence that the enhanced greenhouse effect might have on soil moisture days (days when both soil moisture and temperature are suitable for plant growth).



Soil moisture days measured in 1990 (360 ppm CO_2)

Soil moisture days predicted for 2050 (550 ppm CO_2)

Figure 1.3: The predicted effect of global climate change on "**soil moisture days**" in South Africa, according to The National Biodiversity Institute of South Africa. The top graph shows the measured values in 1990, with the bottom one indicating the predicted values for 2050.

The statements and figures presented above, illustrates the alarming forecast: the climate of the earth is changing more than what can be expected as a result of natural cyclic changes; and human activities could be responsible for the predicted accelerated change. Engineering hydrologists are, amongst other duties, responsible for the determination of peak discharges to be able to size conduits to safely convey the stormwater for given recurrence interval events. All hydrological predictions are indirectly or directly based on historical data. Empirical formulas and deterministic methods were developed and calibrated from known historical data. Statistical predictions are directly based on actual data. The question that arises is whether the historical data still provides an accurate basis from which possible future events can be predicted?

This thesis strives to find an answer to this question and will also try to shed some light on how hydrologists should analyze historical data in the future, taking climate change into consideration.

1.2 Research objectives and methodology

The main research questions that will be posed can be summarized as follows:

- Does climate change models predict an increase in storms at Molteno station (located in the study area), based on 24-hour rainfall events?
- If the above can be found to be true, does it also apply to the general region?
- Can these findings be confirmed through the analysis of short duration rainfall events (historical data)?

The methodology that will be followed in this study will be as follows:

- Literature study. The main aim of the literature study is to give essential background information on the possible effect that rapid climatic changes, possibly as a result of the enhanced greenhouse effect, might have on various processes. The objective is to highlight some possible consequences resulting from the enhanced greenhouse effect. It will be argued that if these processes are carefully monitored, variations from historical trends may be seen as indicators to climatic changes, bearing in mind that long-term variations must be taken into consideration. Various questions will be posed, regarding the potential impacts of climate change, and the possibility of slowing down or reversing the consequences of the enhanced greenhouse effect.

- Some detail will be given on the climate models in general, shortly explaining the principles on which they are built. It is essential to understand the assumptions and base-principles of these models, to be able to interpret their results and their validity. The three models that will be used in this study, Echam, Csiro and Hadam will be discussed briefly.
- The case study will look at the influence of climate change on the intensity of rainfall in the City of Cape Town. The study will be divided into four distinct steps, all striving to highlight possible changes in the intensity of rainfall in the study area. The four steps will be outlined below.
    - <u>Comparison of historical data with forecasted data for Molteno station, for less than 24 hour storm duration.</u> Historical as well as forecasted daily rainfall data (from climate models) will be multiplied by ratios to obtain shorter duration data. These will be compared to theoretical- as well as previously determined IDF (intensity-duration-frequency) curves, to verify whether the forecasted data correspond to IDF curves presently in use.
    - <u>Comparison of historical data with forecasted data for Molteno station, for 24 hour storm duration.</u> Historical as well as forecasted 24-hour rainfall data will be divided into predetermined rainfall ranges (of different magnitude experienced during 24-hour rainfall events) and the percentage of occurrence of events for every range will be determined for both the historical as well as the forecasted data. A comparison of the distribution of rainfall events for the different ranges will then be made between the historical and forecasted data. For example, the percentage of times that a historical 24-hour storm will yield rainfall of between 10 and 15 mm will be determined. Similarly will the percentage of times that the forecasted data will yield rainfall for the same range be determined. The percentage of occurrence of historical rainfall for every rainfall range will then be compared to the corresponding rainfall range's percentage of occurrence for the forecasted data.

- Comparison of historical data with forecasted data for four additional stations near Molteno station, for 24 hour storm duration. Steps similar to those outlined above will be followed for data (historical as well as forecasted) for four additional stations near the study area. The purpose of this will be to attempt to verify the results obtained at Molteno station, with stations near to it. Every rainfall range's percentage of occurrence (for the forecasted data) will be divided by the specific station's corresponding historical percentage of occurrence. This will be done to normalize the data. Any deviation from one will then indicate either an increase in percentage of occurrence (for values larger than one) for the particular rainfall range, or a decrease in percentage of occurrence (for values less than one). The normalizing process will be followed for all four additional stations, as well as for Molteno station. The normalized data will then be added together, and divided by five (for five stations) to obtain regionalized figures.
- Detailed analysis of all rainstorms at Molteno station, for the period 1958 to 2003. The purpose of this step will be to verify whether any trends identified in the preceding steps can already be recognized at Molteno station. Every rainfall event at Molteno for the period from 1958 till 2003 will be analyzed. The purpose of this step of the study will be to try and establish whether the different duration events' maxima recorded every year, are showing any increasing- or decreasing-trend. As we will only be interested in maximum events, a cut-off minimum will be introduced for events of different storm-durations. The second step of the detailed analyses of all data, will be to determine the average of all 5-minute duration events for every year (no cut-off minimum applied). The purpose of this section of the study will be to establish whether the trends identified during the comparison of the historical- and the forecasted-data, can already be recognized for short duration rainfall at Molteno station.

- After the completion of the case study, some indications will be given on how hydrologists should take cognizance of the possible changes to rainfall intensities. Conclusions will be drawn from the study, and recommendations will be made.

2. Literature study

2.1 Climate change indicators

There are various indicators that can be monitored to measure and verify possible climatic changes. In later chapters, we will investigate what the possible effects of climate change could be on amongst others, the coastal zone, biodiversity and water resources. If the impact of climate change on the above mentioned areas and processes are monitored, and changing trends can be identified, these processes could in fact be seen as climate change indicators. In other words, if climate change has an effect on any process, that process, if monitored, can be seen as a climate change indicator. This is of major importance to us, to be able to accurately identify whether climatic changes are experienced in any given area. In this chapter, we will have a short introductory look at some climate change indicators, highlighting changes and trends already experienced worldwide.

Figure 2.1.1 shows the combined land- and sea surface air temperatures (degrees Centigrade) from 1861 to 1998, relative to the average temperature between 1961 and 1990 (adapted from Intergovernmental Panel on Climate change website).

The mean global surface temperature has increased by about 0.3 to 0.6°C since the late 19th century and by about 0.2 to 0.3°C over the last 40 years, which is the period with most reliable data. Recent years have been among the warmest since 1860; the period for which instrumental records are available (Climate change information kit, 1999, with similar graphs obtained from the Intergovernmental Panel on Climate change).

Warming is evident in both sea surface and land-based surface air temperatures. Urbanization in general could have contributed only a small fraction of the overall global warming, although urbanization may have been an important influence in some regions.

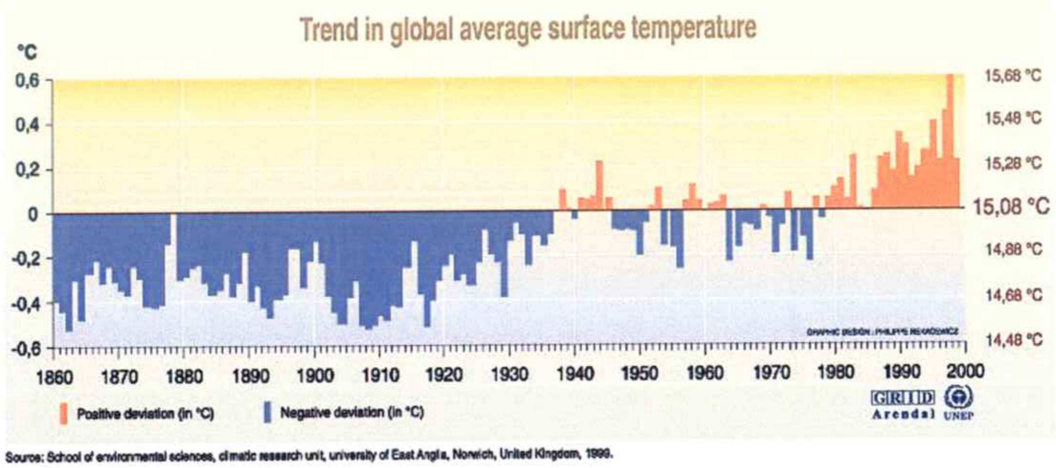


Figure 2.1.1: Observed trends in global average surface temperatures (Intergovernmental Panel on Climate change website)

Precipitation has increased over land at high latitudes of the Northern Hemisphere, especially during the cold season, see Figure 2.1.2. Decrease in precipitation occurred in steps after the 1960s over the subtropics and the tropics from Africa to Indonesia. Precipitation averaged over the Earth's land surface increased from the start of the century up to about 1960, but has decreased since about 1980 (adapted from Intergovernmental Panel on Climate change website).

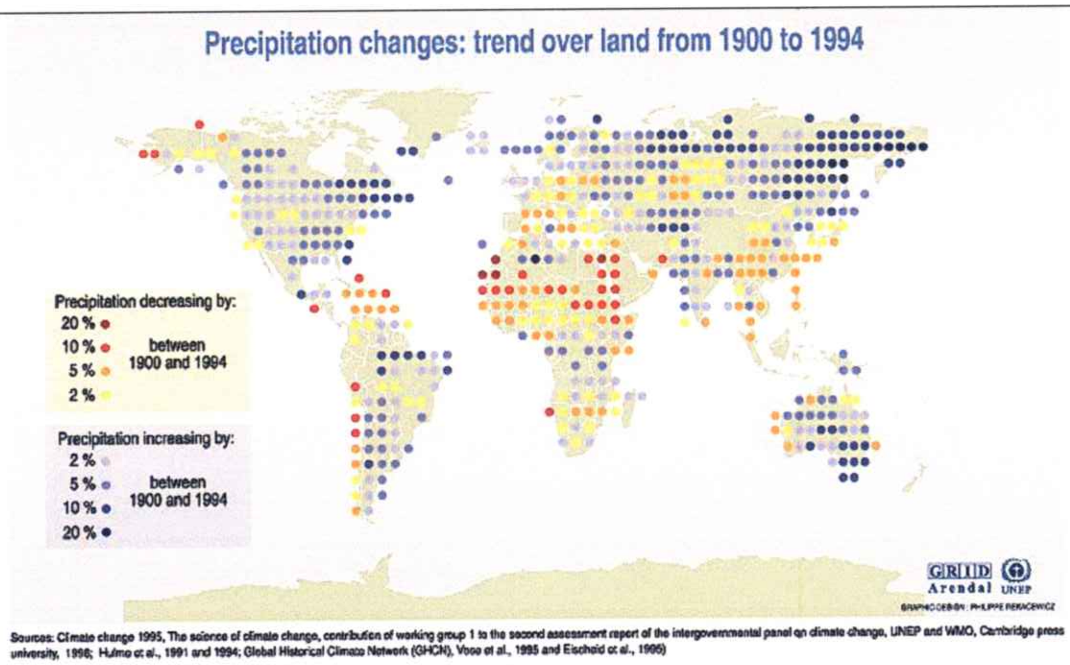


Figure 2.1.2: Precipitation changes: Trend over land from 1900 to 1994 (Intergovernmental Panel on Climate change)

Over the last 100 years, the global sea level has risen by about 10 to 25 cm, refer Figure 2.1.3 (Climate change information kit, 1999). Sea level change is difficult to measure. Relative sea level changes have been derived mainly from tide-gauge data. In the conventional tide-gauge system, the sea level is measured relative to a land-based tide-gauge benchmark. The major problem is that the land experiences vertical movements, and these get incorporated into the measurements. However, improved methods of filtering out the effects of long-term vertical land movements, as well as a greater reliance on the longest tide-gauge records for estimating trends, have provided greater confidence that the volume of ocean water has indeed been increasing, causing the sea level to rise within the given range.

It is likely that much of the rise in sea level has been related to the concurrent rise in global temperature over the last 100 years. On this time scale, the warming and the consequent thermal expansion of the oceans may account for about 2-7 cm of the observed sea level rise, while the observed retreat of glaciers and ice caps may account for about 2-5 cm. Other factors are more difficult to quantify. The rate of observed sea level rise suggests that there has been a net positive contribution from the huge ice sheets of Greenland and Antarctica, but observations of the ice sheets do not yet allow meaningful quantitative estimates of their separate contributions. The ice sheets remain a major source of uncertainty in accounting for past changes in sea level, because of insufficient data about these ice sheets over the last 100 years.

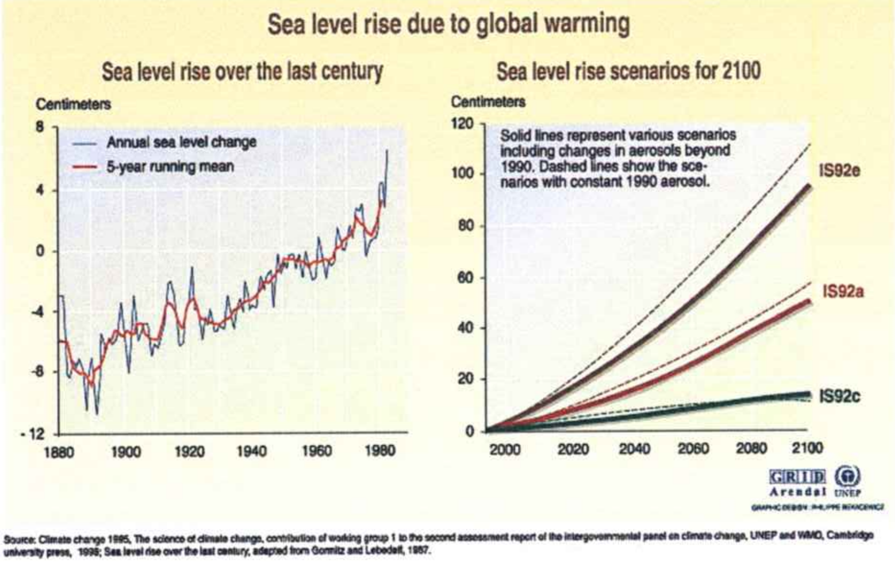


Figure 2.1.3: Sea level rise due to global warming. The graph on the left showing the observed- and the one on the right the predicted scenarios (Intergovernmental Panel on Climate change)

We have now had a look at three important climate change indicators, namely temperature, precipitation and sea level. Any climate change indicator must be of importance, because some indicators may not exhibit measurable changes in certain cases, and researchers may need to look beyond certain indicators to try and establish a trend in a given area. Although a certain researcher's field of interest may be the effect that climate change might have on rainfall, when the predicted rainfall is analyzed, he may find that clear trends towards change are not evident. However, when for instance, air temperature is monitored and predicted temperatures are analyzed, the researcher may find that changes are very likely to occur. These changes could quite possibly influence the rainfall – and various other processes – in the region; hence the importance of understanding the effect that climate change might have on processes which might be considered to fall outside the scope of a specific field of research.

Although the effect of climate change on various processes will be highlighted in the next paragraphs, the main focus remains on rainfall intensities. Various indicators may be analyzed to identify whether a changing climate is experienced or can be expected in a given area, but the obvious important indicator, in the context of this study, is rainfall. The data-sets that were analyzed in this study were historical and expected rainfall depths and the remaining indicators and processes discussed in the study, serves to substantiate the presence of a changing climate.

2.2 The influence of humans on natural climate cycles

The question can be asked whether climate changes (as a result of human's influence) has already occurred, is it something that lies ahead, or are we experiencing climatic changes at present. Although in part already answered in the preceding paragraphs, we will now have a more detailed look at some of the indicators, showing the effect of a changing climate. It must once again be emphasized that natural climatic cycles occurs in nature. These cannot and should not be altered, and our aim is to identify those enhanced changes and their effects, brought about by human activities.

The earth's climate is already adjusting to past greenhouse gas emissions. The climate system must adjust to changing greenhouse gas concentrations in order to keep the global energy balanced. This means that the climate is changing and will continue to change as long as greenhouse gas levels keep rising. The real question is how large the change is likely to be relative to the natural climate fluctuations that human societies and natural ecosystems have learned to adapt to.

Measurement records indicate a warming of 0.3°-0.6°C in global average temperature since 1860 (Intergovernmental Panel on Climate Change). This is in line with model projections of the size of warming to date, particularly when the cooling effect of sulphur emissions is included. But observations are sparse before 1900 and much of the warming occurred between 1910 and 1940, before the largest rise in greenhouse gases. There is clearly more going on than a simple, direct response to emissions. This is to be expected, as the climate is a complicated and chaotic system.

Mean sea level has risen by 10 to 25 cm and mountain glaciers have retreated. As the upper layers of the oceans warm, water expands and sea level rises. Models suggest that a 0.3°-0.6°C warming should indeed result in a 10 to 25 cm sea-level rise (Intergovernmental Panel on Climate Change). But other, harder-to-predict, changes also affect the real and apparent sea level, notably snowfall and ice-melt in Greenland and Antarctica and the slow "rebound" of northern continents freed from the weight of ice age glaciers. Almost all recorded mountain glaciers show a retreat over the past century, but as with sea level, this is unlikely to be only a response to changes in greenhouse gases.

The observed global warming trend is larger than the trends that models indicate, but this could be due to natural variability. A key problem in climate change research is that scientists have no direct way of observing what would have happened if humanity had left the climate alone. There is no direct way of comparing the greenhouse "signal" with the background "noise" of natural climate variability. Instead, this background variability can be estimated by running climate change computer models with constant greenhouse gas levels. The results indicate that the warming trend of 0.3°-0.6°C per century is unlikely to be a chance fluctuation. However, indirect evidence from past climates suggests that these models underestimate the size of natural climate variability, so they may be overestimating the significance of the signal.

Climate models omit many sources of variability that could also cause apparent long-term trends. Current model-based estimates of natural variability do not include the effects of volcanic eruptions, which can cool the global climate temporarily by several tenths of a degree. They are also only beginning to include the effects of long-term changes in the power output of the sun. The sun may have been responsible for relatively cool periods during the 16th, 17th, and 19th centuries (the so-called "Little Ice Ages") when the northern hemisphere may have been about 0.5°C colder than it is today. Some of the warming over the past century (about 20-30% of it, according to some recent model results) may still be a recovery from that time (Climate change information kit, 1999).

The climate however has to be observed over several decades before any climate change signal can be distinguished from natural variability. The longest satellite records are still well under 20 years. Models predict that it should not be possible to detect anything in such a short period, so all that can be said about the satellite data for the moment, is that they are consistent with climate model projections and with evidence from conventional observations. Satellite data do provide global coverage, which helps to validate models and reduce uncertainties.

The evidence suggests that recent changes are unlikely to be entirely due to known sources of natural variability. The pattern of change seems to point to some human influence on climate similar to that projected by climate models and larger than expected from natural fluctuations. This point is not yet settled however, mainly because of uncertainty over the ability of current models to simulate natural variability, realistically. Nevertheless, it is reassuring for many modelers because it suggests that the models are pointing in roughly the right direction!

The earth's climate varies naturally. Each component of this complex system evolves on a different timescale. The atmosphere changes in hours and its detailed behaviour is impossible to predict beyond a few days. The upper layers of the oceans adjust in the course of a few seasons, while changes in the deep oceans can take centuries. The animal and plant life of the biosphere (which influences rainfall and temperature) normally varies over decades. The cryosphere (snow and ice) is slower still: changes in thick ice sheets take centuries. The geosphere (the solid earth itself) varies slowest of all — mountain-building and continental drift (which influences winds and ocean currents) take place over millions of years (Climate change information kit, 1999).

Past natural climate changes offer vital insights into human-induced climate change. Studies of past climates ("paleoclimatology") give a sense of the scale of future changes projected by climate models. They also provide a crucial check on scientists' understanding of key climate processes and their ability to model them.

Systematic global temperature records are available only since 1860. These include land-based air temperature measurements and sea-surface temperature measurements. Such data need to be checked carefully for any biases that may be introduced by changes in observation methods or sites. For example, many meteorological stations have been located in or near cities. As cities grow, they can have a significant warming effect on the local climate. Such effects must be taken into account in estimating recent changes in global temperature.

Studies of earlier climates are based on indirect evidence. Changing lake levels, for example, can reveal the past balance between rainfall and evaporation. Tree-rings, coral, ice-caps, or ocean sediments can all preserve information about the past. Using a combination of measurements, models, and "detective work", scientists convert the quantities they can measure (such as the chemical composition of an ice-core sample) into the physical variables they wish to investigate (such as the Antarctic temperature of 100,000 years ago).

The earth's climate has been dominated by ice ages for the past few million years. It is thought that ice ages are triggered by slow "wobbles" in the earth's axis and its orbit around the sun. These wobbles affect the total amount of energy the planet receives from the sun and in particular its geographic distribution. During an ice age, global temperatures fall by 5°C and ice-sheets advance over much of Europe and North America. Ice ages are separated by warmer "interglacial" periods.

Changes in greenhouse gas concentrations may have helped to amplify ice-age cycles. The small fluctuations in energy arriving from the sun due to the earth's orbital wobbles are not large enough to account for the size of global temperature changes during the ice-age cycles. Ice-core samples show that greenhouse gas levels also varied significantly and may have played an important role in amplifying temperature fluctuations.

Reconstructions of past climates can be used as a check on climate model projections. Comparing a model "prediction" of ice-age climate with the evidence from paleoclimatology provides a crucial check on the model's representation of processes relevant for future climate change. But the paleoclimatic evidence can be ambiguous: some sources suggest that, compared with today, tropical seas were some 5°C colder at the peak of the last ice age, while others suggest only 1-2°C. As a result, separating model errors from uncertainties in the evidence can be difficult (Climate change information kit, 1999).

Abrupt climate variations in the distant past appear to have been traumatic for life on earth. The earth's biological history is punctuated by so-called "mass extinction events" during which a large fraction of the world's species are wiped out. There are many possible reasons for mass extinctions, but the records suggest that some of these events coincided with relatively abrupt changes in climate — similar in magnitude to the kind of change now forecast for the 21st century. Over the next 100 years we may experience conditions unknown since before the ice ages began many millions of years ago.

2.3 Is the changing climate a cause for concern?

According to Professor Will Alexander, emeritus professor from the University of Pretoria, "*there is no evidence to support the view that climate change could cause appreciable environmental damage or increase the frequency and magnitude of floods and droughts in South Africa within the foreseeable future. On the contrary, the beneficial consequences of increased global warming will be greater than the adverse effects*" (Waterwheel, 2004).

In the 1940s, DF Kokot, a Civil Engineer in the then Department of Irrigation undertook a comprehensive study to determine whether or not there had been recent climatic changes that could have had an effect on rainfall and river flow. The results of this study were published in 1948 in a 160-page Irrigation Department memoir titled "*An investigation into evidence bearing on recent climatic changes over southern Africa.*" It contained 418 references, including reports by early travellers and missionaries (Waterwheel, 2004).

Mr Kokot discounted many of the theories that had been advanced for climate changes. He noted for example, that an elaborate theory had been built up to connect known climatic changes with assumed changes in the percentage of carbon dioxide present in the atmosphere, but he remained sceptical.

Mr Kokot's final conclusion was: "*The rainfall record is too short to be of much value in disclosing rainfall trends. It shows, however, that if we take South Africa as a whole there is little evidence of any change. Whilst rainfall in some areas seems to have diminished, in others it appears to have increased*" (Waterwheel, 2004).

Professor Alexander claims that today, more than 50 years later, Mr Kokot's conclusions remain valid and there is still no concrete evidence of large-scale adverse effects of climate change on the environment in South Africa.

Professor Alexander also claims to have assembled the largest and most comprehensive set of meteorological and hydrological data yet analyzed in South Africa. It consists of a total of more or less 12 000 years of data from ±200 gauged sites and eight processes: open-water surface evaporation, concurrent rainfall, aerial rainfall, dam inflow, river flow, flood peak maxima, ground water levels, and the southern oscillation index.

A surprising result from this study was that the mean annual rainfall over South Africa has increased steadily from 497 mm at the beginning of the record in 1921 through to 543 mm at the end of the record in 1999. This is a substantial increase and is in close agreement with the 10% increase reported for the USA since 1910. There were corresponding increases in river flow, open-water surface evaporation and ground water levels (Waterwheel, 2004). Professor Alexander argues that as open water surface evaporation is a function of solar radiation, air temperature and wind, all at water surface level, this identifies global warming as the probable cause of the increases in evaporation, and consequently rainfall, river flow and groundwater levels as well. According to the study, there were no indications of increases in the severity and magnitude of droughts and floods.

The conclusion was made that additional global warming will have a greater beneficial effect than detrimental effect on the natural environment. This is however directly contrary to current views by South African climatologists and environmental scientists, who believe that climate change will have severe impacts on the natural environment.

Professor Alexander's view, as outlined above, evoked major objections and many hydrologists and climatologists raised concerns. Professor Hewitson from the Climate systems analysis group at the University of Cape Town, replied by saying that: "*perhaps the most dangerous attitude to adopt, is to over simplify matters...because of the tremendous importance of the question of climate change to all aspects of society, it is imperative that we examine the issue carefully. Of special importance are the relevant aspects of climate change for any given sector; what are the inter-dependencies of the coupled human-environment system? For example, for an agricultural crop such as maize, changes in dry spell duration and water availability, coupled with increases in temperature would together affect soil moisture, crop stress and vulnerability to crop diseases with significant impacts on productivity. Such combinatory impacts could potentially make a given activity in one region non-viable with further consequences for the economy, employment and quality of life for many people. This example serves to emphasize the extreme importance of careful assessment. Crucially, it must be recognized that as society builds an infrastructure and undertakes activities designed for a given climate, any change in the climate makes the infrastructure sup-optimal, potentially to the point of failure*" (Waterwheel, 2004).

It can be seen that the climate response system is an intricate system, triggered by changes in the global solar energy, which in turn has been altered as a result of human activity. To conclude that an apparent overall increase in available water-resources - on a national scale - as a result of an increase in temperature, will be the overridingly positive outcome of climate change, would be short-sighted, especially in the light of the many alarmingly negative impacts associated with an increase in temperature.

In the following paragraphs, we will highlight some potential impacts climate change may have on various processes. It will be shown that some severe negative impacts can be associated with a changing climate.

2.4 What are the potential impacts of climate change?

Humanity's greenhouse gas emissions are expected to contribure to climatic changes in the 21st century and beyond. These changes will potentially have wide-ranging effects on the natural environment as well as on human societies and economies, refer Figure 2.4.1 (Climate change information kit, 1999). Scientists have made estimates of the potential direct impacts on various socio-economic sectors, but in reality the full consequences would be more complicated because impacts on one sector can also affect other sectors indirectly. To assess potential impacts, it is necessary to estimate the extent and magnitude of climate change, especially at the national and local levels. Although much progress has been made in understanding the climate system and climate change, projections of climate change and its impacts still contain many uncertainties, particularly at the regional and local levels.

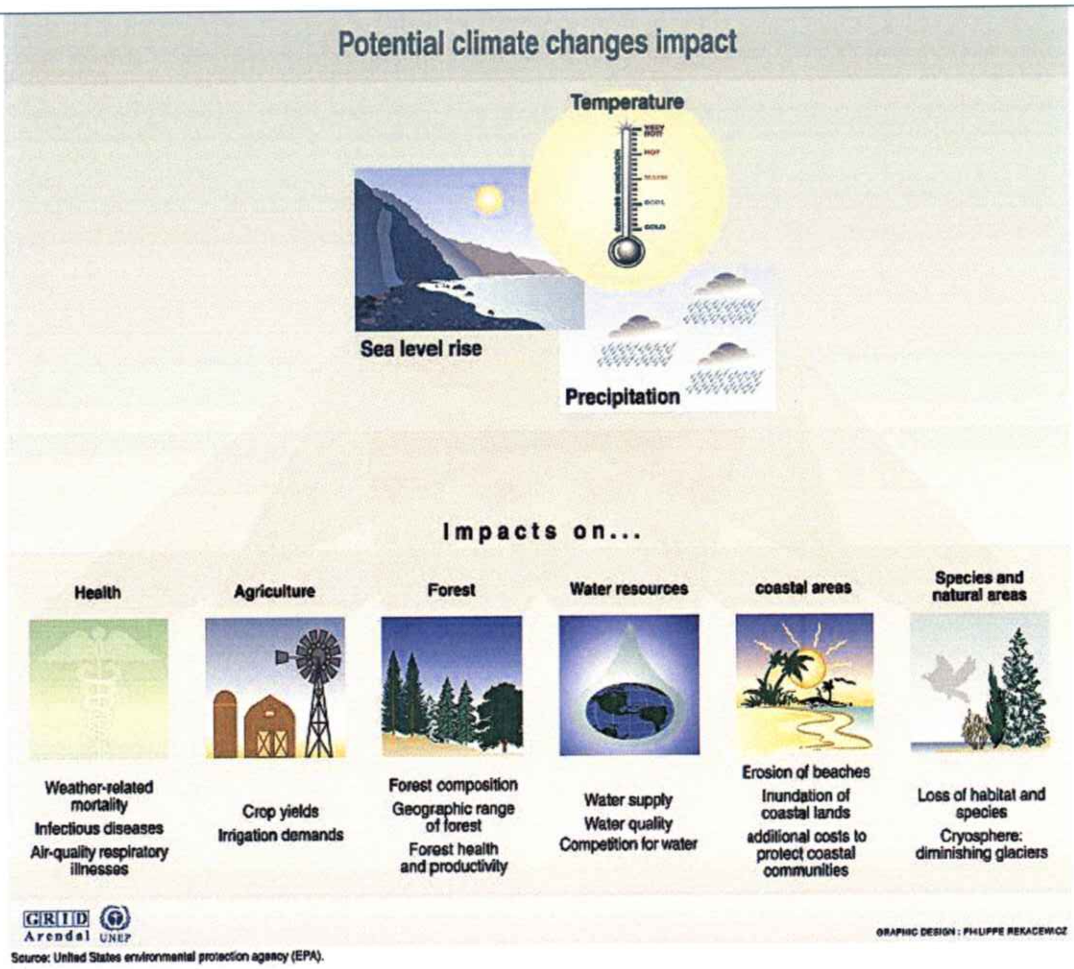


Figure 2.4.1: Potential climate change impacts (Climate change information kit, 1999)

In the next few chapters, the impact of climate change on human and animal health, the coastal zone, biodiversity, water resources and ultimately on hydrological predictions, will be investigated in more detail. Although the impact on human and animal health, the coastal zone, biodiversity and water resources – chapters six to nine - are not directly related to the specific topic for this research, it strives to highlight the importance of the effects of climate change, on a broader scale.

The potential impacts of climate change on hydrological predictions will be shown in chapter 2.9, the case study in chapter 4 and the subsequent recommendations in chapters 5 and 6. These chapters will specifically focus on the effects a changing climate may have on rainfall intensities, and therefore on hydrological predictions.

2.5 What is the impact of climate change on human and animal health? (Climate change information kit, 1999)

Climate change is expected to have wide-ranging consequences for human health. Public health depends on sufficient food, safe drinking water, secure shelter, good social conditions, and a suitable environmental and social setting for controlling infectious diseases. All of these factors can be affected by climate.

Any increase in the frequency or intensity of extreme weather events would pose a threat. Heat waves, flooding, storms, and drought can cause deaths and injuries, famine, the displacement of populations, disease outbreaks, and psychological disorders. While scientists are uncertain how climate change will affect storm frequency, they do project that certain regions will experience increased flooding or drought. In addition, coastal flooding is expected to worsen due to sea-level rise unless sea defenses are upgraded.

Heat waves are linked to cardiovascular, respiratory, and other diseases. Illness and deaths from these causes could be expected to increase, especially for the elderly. A greater frequency of warm or hot weather and of thermal inversions (a meteorological phenomenon that can delay the dispersal of pollutants) may worsen air quality in many cities. On the other hand, milder winters in temperate climates would probably reduce cold-related deaths in some countries.

By reducing fresh water supplies, climate change may affect water resources and sanitation. This in turn could reduce the water available for drinking and washing. Water scarcity may force people to use poorer quality sources of fresh water, such as rivers, which are often contaminated. All of these factors could result in an increased incidence of diarrhoeal diseases.

Food security may be undermined in vulnerable regions. Local declines in food production would lead to more malnutrition and hunger, with long-term health consequences, particularly for children.

The geographical distribution of species that transmit disease may be altered. In a warmer world, mosquitoes, ticks, and rodents could expand their range to higher latitudes and higher altitudes. Approximately 45% of the world's human population presently lives in regions suitable for malaria transmission. Climate change impact models suggest that the largest changes in the potential for disease transmission will occur at the fringes — both in terms of latitude and altitude — of the current malaria risk areas. Generally, people in these border areas will not have developed immunity to the disease. The seasonal transmission and distribution of many other diseases that are transmitted by mosquitoes and by ticks may also be affected by climate change.

The above viewpoint is supported by the South African Weather Bureau. There are several important insect-carried diseases of humans and livestock which are sensitive to the climate. A small increase in temperature would allow, for instance, malaria to spread into areas which are currently malaria-free, and would increase its severity in areas where it already occurs (WeatherSA).

Projected increases in the inter-annual variability of climate would have marked implications for the impact of seasonal epidemic diseases such as malaria. In general, control and mitigation activities for such diseases are planned around mean expected levels in any one year. Significant inter-annual variation impedes intervention and mitigation because of the impact on national budgets (which plan for mean circumstances) and lags that occur in relation to responses to climatically induced epidemic situations (United Nations Environment programme).

There is a long list of other potential health effects. Asthma, allergic disorders, and cardio respiratory diseases could result from climate-induced changes in the formation and persistence of pollens, spores, and certain pollutants.

People will have to adapt or intervene to minimize these enhanced health risks. Many effective measures are available. The most important, urgent, and cost-effective is to rebuild the public health infrastructure in countries where it has deteriorated in recent years. Many diseases and public health problems that may be exacerbated by climate change can be effectively prevented with adequate financial and human resources. Adaptation strategies can include infectious disease surveillance, sanitation programmes, disaster preparedness, improved water and pollution control, public education directed at personal behavior, training of researchers and health professionals, and the introduction of protective technologies (such as housing improvements, air conditioning, water purification, and vaccination).

Assessing the potential health effects of climate change involves many uncertainties. Researchers must consider not only future scenarios of climate change but many non-climate factors as well. For example, trends in socio-economic conditions can have a major affect on a population's vulnerability. Clearly, poorer communities will be more vulnerable to the health impacts of climate change than rich ones.

In much of the world, life expectancy is increasing; in addition, infant and child mortality in most developing countries is dropping. Against this positive backdrop, however, there appears to be a widespread increase in new and resurgent vector-borne and infectious diseases, such as dengue, malaria, hantavirus, and cholera. In addition, the percentage of the developing world's population living in cities is expected to increase from 25% (in 1960) to more than 50% by 2020, with percentages in some regions far exceeding these averages. These changes will bring benefits only if accompanied by increased access to services such as sanitation and potable water supplies; they can also lead to serious urban environmental problems, including air pollution (e.g., particulates, surface ozone, and lead), poor sanitation, and associated problems in water quality and potability, if access to services is not improved.

Climate change could affect human health through increases in heat-stress mortality, tropical vector-borne diseases, urban air pollution problems, and decreases in cold-related illnesses. Compared with the total burden of ill health, these problems are not likely to be large. In the aggregate, however, the direct and indirect impacts of climate change on human health do constitute a hazard to human population health, especially in developing countries in the tropics and subtropics; these impacts have considerable potential to cause significant loss of life, affect communities, and increase health-care costs and lost work days (The Regional impacts of Climate change, Intergovernmental Panel on Climate change).

2.6 What is the impact of climate change on the coastal zone? (Climate change information kit, 1999)

The global average sea level has risen by 10 to 25 cm over the past 100 years. It is likely that much of this rise is related to an increase of 0.3-0.6°C in the lower atmosphere's global average temperature since 1860.

According to the Climate change information kit (1999), models project that sea levels will rise another 15 to 95 cm by the year 2100 (with a "best estimate" of 50 cm). This will occur due to the thermal expansion of ocean water and an influx of freshwater from melting glaciers and ice. The projected rise is two to five times faster than the rise experienced over the past 100 years. The rate, magnitude, and direction of sea-level change will vary locally and regionally in response to coastline features, changes in ocean currents, differences in tidal patterns and sea-water density, and vertical movements of the land itself. Sea levels are expected to continue rising for hundreds of years after atmospheric temperatures stabilize.

Coastal zones and small islands are extremely vulnerable. Coasts have been modified and extensively developed in recent decades and thus made even more vulnerable to higher sea levels. Developing countries with their weaker economies and institutions face the gravest risks, but the low-lying coastal zones of developed countries could also be seriously affected. Given the present degree of protection, a sea-level rise of one metre would cause estimated land losses of 0.05% in Uruguay, 1% in Egypt, 6% in the Netherlands, 17.5% in Bangladesh, and up to about 80% for Atoll Majuro in the Marshall Islands.

Flooding and coastal erosion would worsen. Salt-water intrusion will reduce the quality and quantity of freshwater supplies. Higher sea levels could also cause extreme events such as high tides, storm surges, and seismic sea waves (tsunamis) to reap more destruction. Flooding due to storm surges already affects some 46 million people in an average year, most of them in developing countries. Studies suggest that this figure could increase to 92 million with a 50 cm sea-level rise, and to 118 million with a one-metre rise.

Sea-level rise could damage key economic sectors. A great deal of food is produced in coastal areas, making fisheries, aquaculture, and agriculture particularly vulnerable. Other sectors most at risk are tourism, human settlements, and insurance (which has already suffered record losses recently due to extreme climate as well as other events). The expected sea-level rise would inundate much of the world's lowlands, damaging coastal cropland and displacing millions of people from coastal and small-island communities.

Sea-level rise could threaten human health. The displacement of flooded communities, particularly those with limited resources, would increase the risk of various infectious, psychological, and other illnesses. Insects and other transmitters of disease could spread to new areas. The disruption of systems for sanitation, stormwater drainage, and sewage disposal would also have health implications.

Valuable coastal ecosystems will be at serious risk. Coastal areas contain some of the world's most diverse and productive ecosystems, including mangrove forests, coral reefs, and sea grasses. Low-lying deltas and coral atolls and reefs are particularly sensitive to changes in the frequency and intensity of rainfall and storms. Coral will generally grow fast enough to keep pace with sea-level rise but may be damaged by warmer sea temperatures.

Ocean ecosystems may also be affected. In addition to higher sea levels, climate change could reduce sea-ice cover and alter ocean circulation patterns, the vertical mixing of waters, and wave patterns. This could have an impact on biological productivity, the availability of nutrients, and the ecological structure and functions of marine ecosystems. Changing temperatures could also cause geographical shifts in biodiversity, particularly in high-latitude regions, where the growing period should increase (assuming light and nutrients remain constant).

Various natural forces will influence the impact that higher sea levels will have. Coastal areas are dynamic systems. Sedimentation, physical or biotic defenses (such as coral reefs), and other local conditions will interact with rising sea-water. For example, freshwater supplies in coastal zones will be more or less vulnerable depending on changes in freshwater inflows and the size of the freshwater body. The survival of salt marshes and mangrove forests will depend in part on whether the rate of sedimentation is greater than or less than the rate of local sea-level rise. Sedimentation is more likely to exceed sea-level rise in sediment-rich regions such as South Africa, where strong tidal currents redistribute sediments, than in sediment-starved environments such as the Caribbean.

Human activities will also play a role. Roads, buildings, and other infrastructure could limit or affect the natural response of coastal ecosystems to sea-level rise. Pollution, sediment deposits, and land development will influence how coastal waters respond to, and compensate for, climate change impacts.

Coastal zones are characterized by a rich diversity of ecosystems and a great number of socioeconomic activities. Coastal human populations in many countries have been growing at double the national rate of population growth. It is currently estimated that about half of the global population lives in coastal zones, although there is large variation among countries. Changes in climate will affect coastal systems through sea-level rise and an increase in storm-surge hazards and possible changes in the frequency and/or intensity of extreme events (The Regional impacts of Climate change, Intergovernmental Panel on Climate change).

It was mentioned in Chapter 2.1 that changes in sea level is difficult to monitor. Various complicating factors were also given in the preceding paragraphs, highlighting the intricacy of this process. Although changes in sea level may not have a direct impact on rainfall intensities, the rising sea level may influence some hydraulic structures that are situated close to the sea, adding yet another changing design consideration for engineers. Changes in sea level can also, as explained earlier, be monitored to serve as a climate change indicator. In light of the above, it is apparent that the changing sea level is of major importance to engineers.

2.7 What is the impact of climate change on biodiversity? (National Biodiversity institute, 2005)

Dr Bob Scholes, a systems ecologist and a Fellow of the CSIR, said that "*...there are strong indications that the exceptionally rich biodiversity of southern Africa is vulnerable to climate change...*" (National Biodiversity institute, 2005).

The global climate has changed repeatedly in the distant past. Although these events are typically associated with a degree of species loss, overall they often mark the beginning of a burst of new species. But two features make the current human-induced climate change event different and threatening: the rate at which the climate is projected to change is about ten times faster than in the past; and the landscape through which the plants and animals must migrate has been radically fragmented by human activities.

The succulent karoo of the west-coast of South Africa and Namibia is particularly threatened by climate change. It is home to about 3 000 species of plants that occurs nowhere else. A large fraction of the world's succulent flora comes from here. The area covered by the unique dry, winter-rainfall climate is projected to shrink or completely disappear under some future climate scenarios.

The fynbos of the southern Cape, the world's smallest and richest plant kingdom on a per area basis, is now mostly confined to the rugged mountains of the region, since the valleys have been converted to agriculture. The question that is asked is how can plants, birds and reptiles migrate in pursuit of their preferred climate, when there are wide barriers of unsuitable habitat between their present location and their future distribution?

The vegetation of South Africa is so rich and varied that, when discussing plant distribution, it is convenient to refer to broad ecological regions. We can call these regions biomes, and they are characterized by particular climates and vegetation types. Ecologists have described seven South African biomes, namely Desert, Forest, Fynbos, Grassland, Nama-Karoo, Savanna and Succulent Karoo (see Figure 2.7.1).

- The Fynbos and Succulent Karoo biomes are found in the western parts of South Africa where rain falls in winter.
- Nama-Karoo vegetation, with its typical hardy bushes and grasses, covers much of the arid interior.
- In the summer rainfall areas, Grassland dominates much of the highveld where frost restricts the growth of trees.
- The coastal and lowveld regions are warm enough in winter to support Savanna vegetation.
- The smallest biomes are the Forest Biome in the southern Cape and a tiny area of true Desert in the extreme north-west of the Northern Cape.

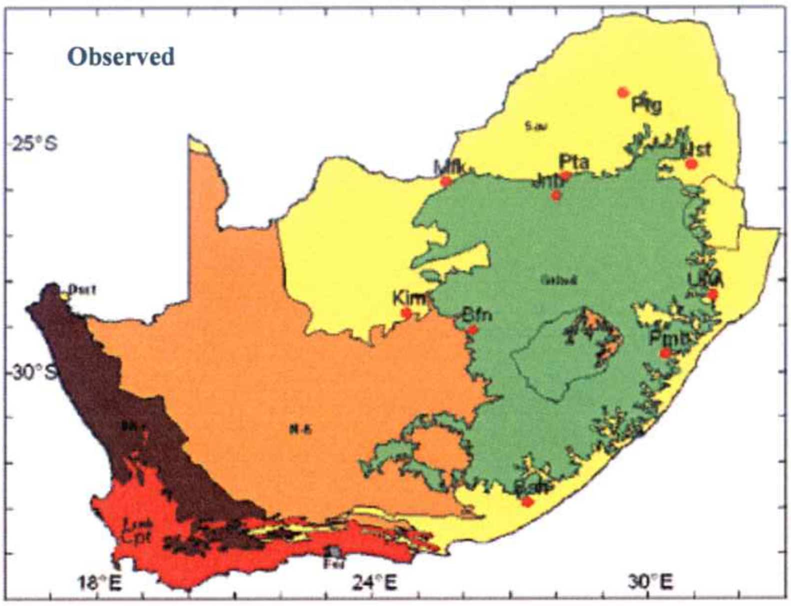
According to climate models, within 50-100 years the biomes as we know them will have been reduced to 35-55% of their present area. Climatic conditions in the rest of the country will be unlike anything experienced today.

From the point of view of plant conservation, one of the greatest challenges is how climate change may affect plant biodiversity "hotspots". These areas are unusually rich in species but are highly threatened by human activities. Hotspots may also have a number of endemic species, which have such restricted natural distributions that they are found in that particular area and nowhere else on Earth!

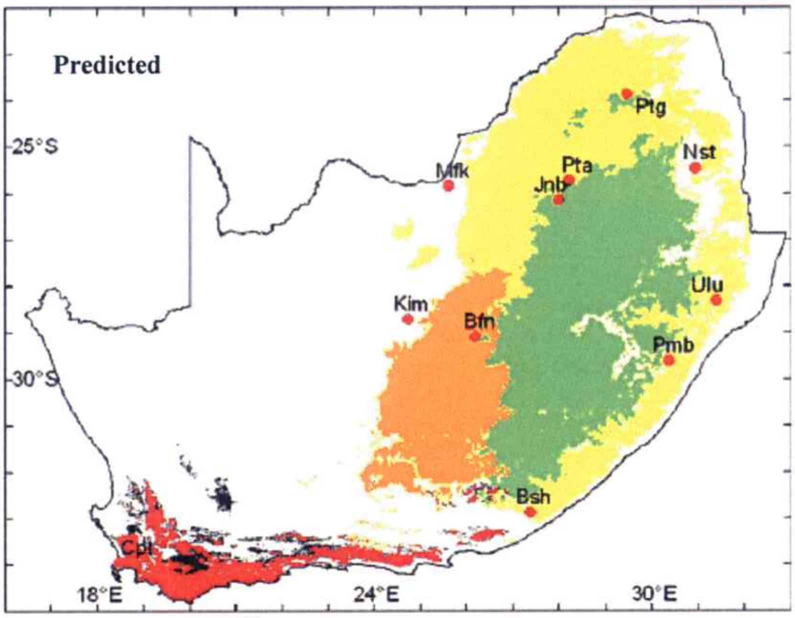
One such global hotspot is the Succulent Karoo Biome, which has the richest succulent flora in the world. These plants live on the edge of survival, completely dependent on low but fairly reliable winter rainfall. If the climate of this region becomes any drier, the effects on the entire biome will be devastating.

Figure 2.7.1, shows the potential effect of global climate change on the biomes of South Africa (National Biodiversity institute, 2005). The alarming results once again highlight the negative effect climate change could have. Rainfall is obviously dependent on evaporation as well as evapo-transpiration. It follows that a loss of biodiversity or overall loss of plant-coverage, could lead to decreasing rainfall, consequently leading to even less plant-coverage. This snowball effect has an obvious impact on rainfall and therefore rainfall intensities.

The biomes of South Africa as mapped in the year 2000



The biomes of South Africa in the year 2050
Predictions are based on climate changes brought on by an increase in the concentration of atmospheric carbon dioxide to 550 ppm



White areas represent climatic conditions not encountered in South Africa today

Figure 2.7.1: The potential effect of global climate change on biodiversity, showing the observed (top graph) as well as predicted scenarios (National Biodiversity institute, 2005)

2.8 What is the impact of climate change on water resources? (Climate change information kit, 1999)

In certain areas, climate change could lead to more precipitation, but also to more evaporation. In general, this acceleration of the hydrological cycle will result in a wetter world. The question is, how much of this wetness will end up where it is needed?

Precipitation will probably increase in some areas and decline in others. Climate models are still unable to make precise regional predictions. In addition, the hydrological cycle is extremely complex; as explained at the end of the previous chapter, a change in precipitation may affect surface wetness, reflectivity, and vegetation, which then affect evapo-transpiration and cloud formation, which in turn affect precipitation. Meanwhile, the hydrological system is also responding to other human activities such as deforestation, urbanization, and the over-use of water supplies.

Changing precipitation patterns will affect how much water can be captured. Several models suggest that downpours will become more intense. This would increase floods and runoff while reducing the ability of water to infiltrate the soil. Changes in seasonal patterns may affect the regional distribution of both ground and surface water supplies.

The drier the climate, the more sensitive is the local hydrology. Relatively small changes in temperature and precipitation could cause relatively large changes in runoff. Arid and semi-arid regions will therefore be particularly sensitive to reduced rainfall and to increased evaporation and plant transpiration.

Reservoirs and wells would be affected. Changes at the surface would influence the recharging of groundwater supplies and, in the longer term, aquifers. Water quality may also respond to changes in the amount and timing of precipitation.

New patterns of runoff and evaporation will also affect natural ecosystems. Freshwater ecosystems will respond to altered flood regimes and water levels. Changes in water temperatures and in the thermal structure of fresh waters could affect the survival and growth of certain organisms, and the diversity and productivity of ecosystems. Changes in runoff, groundwater flows, and precipitation directly over lakes and streams would affect nutrients and dissolved organic oxygen, and therefore the quality and clarity of the water.

Rising seas could invade coastal freshwater supplies. Coastal aquifers may be damaged by saline intrusion, as salty groundwater rises. The movement of the salt-front up estuaries would affect freshwater pumping plants upriver.

Reduced water supplies would place additional stress on people, agriculture, and the environment. Regional water supplies, particularly in developing countries, will come under many stresses in the 21st century. Climate change will exacerbate the stresses caused by pollution and by growing populations and economies. The most vulnerable regions are arid and semi-arid areas, some low-lying coasts, deltas, and small islands.

One of the great pressures on water resources is increasing human populations, particularly growing concentrations in urban areas. Figure 2.8.1 shows the impact of expected population growth on water usage by 2025, based on the UN mid-range population projection (Climate change information kit, 1999). It uses the current rate of water use per person without taking into account possible increases in water use due to economic growth or improvements in water use efficiency. The regions most vulnerable to domestic water shortages include those where access to water is already limited, the population is growing rapidly, urban centers are spreading, and the economy is burdened by financial problems and a lack of skilled workers. Even if the world maintained the pace of the 1990s in water-supply development, this would not be enough to ensure that everyone had access to safe drinking water by the year 2025.

Improved water resource management can help to reduce vulnerabilities. New supplies must be developed and existing supplies used more efficiently. Long-term management strategies should include: regulations and technologies for directly controlling land and water use, incentives and taxes for indirectly affecting behavior, the construction of new reservoirs and pipelines to boost supplies, and improvements in water-management operations and institutions. Other adaptation measures can include removing levees to maintain flood plains, protecting waterside vegetation, restoring river channels to their natural form, and reducing water pollution.

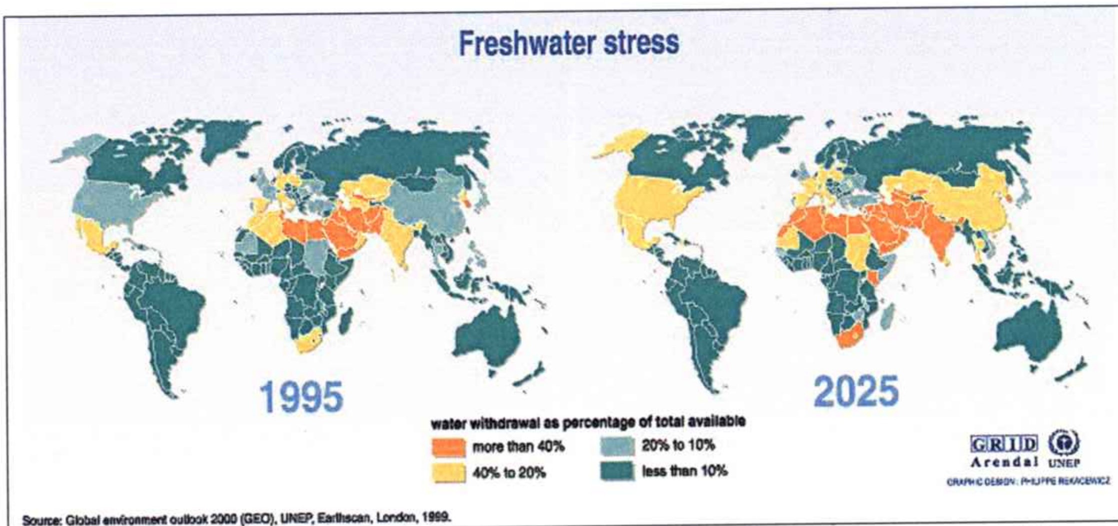


Figure 2.8.1: Current (1995) and predicted (2025) freshwater stresses (Climate change information kit, 1999)

South Africa faces a number of problems related to the efficient utilization of the country's scarce water resources. These problems are exacerbated during dry seasons and drought periods when rural water supply schemes fail, river ecosystems endure severe stress and water pollution becomes critical and extremely difficult to manage.

One of the greatest potential impacts of climate change on human society is through its effect on freshwater resources. The most critical factor associated with climate change impact is the availability of water resources. People dependent on river basins and wetlands face losses of freshwater biodiversity and a reduction in ecosystems services, such as water supply, water purification and flood control. Communities dependent on agriculture and subsistence farming face chronic food shortages, economic and livelihood constraints.

Climate change will persist for many centuries, due to the long life of greenhouse gases in the atmosphere and the long time required for transfer of heat from the atmosphere to the deep oceans; even with quick action to curtail emissions, the effects of our current activity will be felt for hundreds of years. There is already a growing scientific understanding that the conservation and sustainable use of freshwater resources can no longer be achieved without taking climate change into account.

Water plays a complex and multi-facetted role in both human and natural systems. It is an issue that cuts across many sectors such as agriculture, energy, human settlements, livelihoods, tourism, health, industry, recreation, wildlife, and forestry.

Traditionally, water management has focused on the direct provision of water for people to drink, grow their food and support industries. However, as water is a priority resource, there is now a need to understand its actual and potential sustainability from a regional and local perspective in the context of the watershed as the system of analysis. Small changes in the ecological system may have significant and dynamic responses on water quality, quantity and distribution.

The world and South Africa are struggling with freshwater management and sustainability. Many areas face increasing water stress, millions of people remain without access to basic water services and even more millions die annually from preventable water related diseases. Human induced impacts and environmental degradation are placing increased stress on existing and future water resources.

Climate change will affect both water demand (related to higher temperatures) and water supply (the balance of CO_2 enrichment, evapo-transpiration and precipitation) The major effect of climate change on Africa's water systems will be through changes in the hydrological cycle, the balance of temperature and rainfall. There is some concern that the negative impacts of climate change on water supply could actually be larger and the gains smaller than has previously been reported.

According to the Intergovernmental Panel on Climate Change Second Assessment Report (1995), changes in climate will lead to an intensification of the global hydrological cycle and could have major impacts on regional water resources.

Water resources are inextricably linked with climate. Therefore the prospects of global climate change have serious implications for water resources and regional development. Efforts to provide adequate water resources for Africa already confront a number of challenges, including population pressure, problems associated with land use such as erosion or siltation, and possible ecological consequences of land-use change on the hydrological cycle. Climate change will make addressing these problems even more complex.

Water supply undoubtedly is a most important resource for Africa's social, economic, and environmental well being. Currently, about two-thirds of the rural population and one-quarter of the urban population are without safe drinking water, and even higher proportions lack proper sanitation. Climate change will likely make the situation more adverse. The greatest impact will continue to be felt by the poor, who have the most limited access to water resources. Table 2.8.1, highlights some of the affects of climate change on Water Resources (DWAF, 2001).

Table 2.8.1: Affects of climate change on Water Resources (DWAF, 2001)

Climate Change	**Effect**	**Impact**
CO_2 enrichment	Increased photosynthesis; reduced transpiration	Increased water use efficiency
Increased temperature	Faster plant growth, increased transpiration. Increased evaporation from lakes and reservoirs, reduced runoff and reduced groundwater recharge, higher demand for water for irrigation, bathing and cooling	Changes in water yields, higher stress ion water delivery systems during peak loads
Change in seasonal precipitation	Change in soil moisture, change in river runoff and groundwater recharge	Changes in projected yields of reservoir systems, changes in water quality
Change in spatial patterns of temperature and precipitation	Shift in basin hydrology (Surplus and deficit regions)	Changes in infrastructure to supply water
Change in variability of precipitation (Daily and inter-annual)	Changes in water stress between rainfall events, changes in peak runoff	Increased requirement for storage of water supply systems
Changes in drought hazard	Changes in seasonal water stress or off season water replenishment	Altered risk water resources
Change in flood hazard	Change in risk in flood plain, change in area affected	Altered risk water resources, change in reservoir operations

The climate in South Africa is typically warm and dry, with winter temperatures rarely falling below 0°C, and summer maxima frequently above 35°C. The country also falls within the subtropical belts of high pressure, making it dry, with an abundance of sunshine. The wide expanses of ocean on three sides of South Africa have a moderating influence on its climate, although gale force winds frequently occur on the coastlines. South Africa lies within a drought belt with an average annual rainfall of only 464 mm (this is slightly less than the figure provided by Professor Alexander, refer chapter 2.3 of this study), compared to a world average of 857 mm. Twenty-one per cent of the country has an annual rainfall of less than 200 mm, 48 per cent between 200 and 600 mm, while only 30 per cent records more than 600 mm. In total, 65 per cent of the country has an annual rainfall of less than 500 mm (DWAF, 2001).

Studies in South Africa have shown that there has been more than a 1°C increase in temperature over South Africa since the beginning of the century (Hulme, 1996; Mason and Jury, 1997). South Africa's rainfall is erratic in distribution and variable between years. Most of the country is arid and subject to droughts and floods. South Africa's industrial, domestic and agricultural users are highly dependent on a reliable supply of water. Even without climate change, South Africa is predicted to have exhausted its surface water resources early in the 21st century. A reduction in rainfall amount or reliability, or an increase in evaporation (due to higher temperatures) would exacerbate this situation. The arid and semi-arid regions, which cover nearly half of South Africa, are particularly sensitive to changes in precipitation because the fraction of rainfall that is converted to runoff or percolation to groundwater is small. Equally important consequences of global warming are the potential changes in the intensity and seasonality of rainfall. Increased convective activity could increase the frequency and intensity of rainfall events, augmenting runoff volumes and potentially causing higher soil losses.

The severity of these changes will depend on the effects of increased CO_2 concentrations, altered precipitation and soil moisture, and increased temperatures. CO_2 concentrations will probably increase to 460-550ppm by 2050, compared to about 350 ppm at present. CO_2 enrichment in the atmosphere is likely to reduce the rate at which plants transpire, resulting in an increase in water use efficiency.

Increased temperatures increase the atmospheric demand for water, both evaporation from soils and open water and transpiration from plants. The extent to which precipitation offsets the increased evapo-transpiration demand is highly uncertain in Africa.

The region faces the following potential impacts of climate change (DWAF, 2001):

- A 10-20 % decrease in summer rainfall over South Africa's central interior
- An increase in the intensity and frequency of floods and droughts
- A gradual and linear increase in temperature, (with rising CO_2 levels) reaching 1.5^0C hotter than present by the year 2050.

Several water resource strategies have been identified to adapt to climate change. Some of these are highlighted in Table 2.8.2 (DWAF, 2001)

Table 2.8.2: Water resource strategies to adapt to changing climates (DWAF, 2001)

Type of Adaptation	Example of Water Resource Strategies
Anticipatory Adaptation	New water supplies Combined use of groundwater and surface supplies Increase recycling and reuse of waste water Flood protection, flood plain management, warning and evacuation Drought response planning and preparedness Better operation of existing water supplies
Institutional and Regulatory Adaptation	Comprehensive river basin and lake/reservoir management plans that address climate change along with future growth and other management challenges Integrated planning with other sectors Regional co-operation in transboundary water basins, share lessons learned in water management, Community and participatory water resource management Facilitate water markets that encourage conservation and transfers between users and among suppliers
Research and Education	Public awareness about climate change and freshwater issues Water resource monitoring and modelling Water saving technology, especially for irrigation Water treatment technology
Development Assistance for Capacity Building	Flexible water management systems Decrease current water pollution Increase prices to ensure full cost recovery Optimal water system operational rules Rehabilitation of existing systems Water Demand Management

The degree to which societies and institutions can adapt to climate change will depend on their ability to manage water resource supply and demand. Water resource management has traditionally focused on the supply side management. Only recently has demand side water management become a viable alternative strategy. Societies that are able to implement both resource supply side and demand side management strategies are likely to be more adaptive to climate change than those societies that are unable to do so. The ability to adapt to climate change also depends much on the institutional capacity to develop and implement such strategies, and is largely a function of the socio-economic, political, legal and institutional setting in which such institutions operate.

The goals of sustainable water management and conservation are unlikely to be achieved without taking climate change into account. Information about the consequences of climate change on specific water resources and river basins is sorely needed to allow water resource planners and managers to integrate changes in climate into their planning and management efforts. It is generally understood, though, that removing the existing pressures on water resources and improving their resiliency is the most effective method to cope with the adverse effects of climate change. Water resources play an important role in the global carbon cycle and wetlands in particular are a significant storehouse of carbon. However, when these resources (wetlands) are converted, they emit large quantities of carbon dioxide and other greenhouse gases.

Conserving, maintaining, or rehabilitating freshwater ecosystems is therefore a viable element to an overall climate change mitigation strategy. This will be discussed further in chapter 2.10, where the potential of slowing down or reversing the climatic changes will be investigated.

2.9 What is the impact of climate change on hydrological predictions? (Climate change information kit, 1999)

The climate varies naturally on all time-scales. Variations can be caused by external forces such as volcanic eruptions or changes in the sun's energy output. They can also result from the internal interactions of the climate system's various components — the atmosphere, oceans, biosphere, ice cover, and land surface. These internal interactions can cause fairly regular fluctuations, such as the El Niño phenomenon, or apparently random changes in climate.

Natural variability often leads to climate extremes and disasters. On time-scales of days, months, and years, weather and climate variability can produce heat waves, frosts, floods, droughts, severe storms, and other extremes. A climate extreme is a significant departure from the normal state of the climate system, irrespective of its actual impact on life or the earth's ecology. When a climate extreme has a major adverse impact on human welfare, it is called a climatic disaster. In some parts of the world climatic disasters occur so frequently that they may be considered part of the norm. It is possible that greenhouse gas-induced climate change will alter the frequency, magnitude, and character of both climate extremes and climatic disasters.

Every region of the world experiences record-breaking climate extremes from time to time. In 1995, for example, summer heat-waves affected both the US Midwest and the Indian sub-continent. More than 700 people died from heat stress in the US; 500 died in northern India when June temperatures soared to 50 degrees Celsius. Earlier that year, river flooding in the Netherlands caused the evacuation of over 200,000 people and almost half a million livestock. It was the worst flooding since the Dutch sea dikes failed in 1953. In the first decades of the last century, a trend towards increased drought in the North American Midwest culminated in the "Dust Bowl" decade of the 1930s, after which conditions eased. More recently, annual rainfall over the Sahel zone of northern Africa during nine of the years since 1970 has dropped more than 20% below the average prevailing during this century's first seven decades; those previous 70 years saw only one extreme of this magnitude.

Do today's frequent reports of record-breaking events mean that climate extremes are becoming more common? According to the Intergovernmental Panel on Climate Change, there are "*...inadequate data to determine whether consistent changes in climate variability or weather extremes have occurred over the 20th century*". There have been some regional trends but "*some of these changes have been toward greater variability; some have been toward lower variability*". It may simply be that people are much more aware of extreme events because the communications revolution has made news and information so much more widely available than ever before.

Increased human vulnerability is transforming extreme events into more climatic disasters. People in many parts of the world are being forced to live in more exposed and marginal areas. Elsewhere, high-value property is being developed in high-risk zones. This has been reflected in the severe pounding that the international insurance industry has received from a series of "billion dollar" storms since 1987.

In the future, global climate change may significantly affect the frequency, magnitude, and location of extreme events. Any shift in mean climate will almost inevitably affect the frequency of extreme events. In general, more heat-waves and fewer frosts could be expected, and more intense rainfalls may lead to increased flooding in some regions. However, extreme events last for a relatively short time and are usually a local experience, making it difficult for scientists to predict how these events might respond to climate change. For example, a warming of the tropical oceans would by itself be expected to increase the frequency, and perhaps the severity, of tropical cyclones. But other factors, such as changing winds or storm tracks, might offset this effect at the local level. In any case, growing human vulnerability to climate extremes, combined with the uncertainties of climate change, clearly offers cause for concern.

While extreme events are inherently abrupt and random, the risks they pose can be reduced. Improved preparedness planning is urgently needed in many parts of the world, with or without climate change. Better information, stronger institutions, and new technologies can minimize human and material losses. For example, new buildings can be designed and located in ways that minimize damage from floods and tropical cyclones, while sophisticated irrigation techniques can protect farmers and their crops from droughts.

Scientists cannot state with certainty that today's extreme events result from climate change. They simply do not understand the climate system and the effects of greenhouse gas emissions well enough to conclude that particular events are linked to the general problem (it is possible that in future decades they may look back and realize with the benefit of hindsight that certain events indeed were linked). Nevertheless, monitoring and studying extreme events, and learning how to predict and cope with them, must be a priority.

While we often think of climate in terms of averages, the extremes are at least as important in determining a region's climate. For example, Cape Town and Laingsburg have nearly the same annual average temperature, but the temperature in Laingsburg exhibits much greater seasonal variability. Consequently the two centers have different climates[1].

When considering climate change predictions, we also tend to focus on means; particularly the number of degrees average global temperatures is expected to rise. But most of the potential damaging consequences relating to climate change are associated with extremes — the number of heat waves, floods, or severe storms, for example. Since extreme weather events hold great potential for loss of life and property, it is important to understand what impact global warming may have on their occurrence.

It remains very difficult to assess the impact of global warming on extreme weather events, in large part because this analysis depends greatly on regional forecasts for global warming. Global warming will almost certainly have different effects on different regions of the Earth, so areas will not be equally susceptible to increased or more intense extreme weather events. Although regional climate forecasts are improving, they are still uncertain. However, we can be fairly certain that a warmer atmosphere will result in a greater number of extreme heat waves. Additionally, a

[1] In addition to the seasonal variability of the annual average temperature of two centers, the storm producing mechanisms also differ between these two centers, resulting in different climatic conditions

warmer atmosphere can hold more moisture, so changes in the hydrological cycle could alter flood and drought patterns.

One of the most important physical consequences of a warmer atmosphere is an increased capacity to hold moisture. According to the Clausius-Clapeyron relation, the amount of water vapor that can be stored in the atmosphere increases rapidly with temperature. A warmer planet is also most likely a wetter planet, as more evaporation could occur.

An increase in the frequency or intensity of floods would be catastrophic in several places around the world. Perhaps no country is more vulnerable than Bangladesh. Over 17 million people live at an elevation of less than 3 ft (±1 m) above sea level, and millions more inhabit the flat banks of the Ganges and Brahmaputra Rivers. Past floods have displaced millions in Bangladesh, and increased flooding there would have tragic results. Other nations, including China and Vietnam, have experienced floods killing thousands and causing billions in property damage within the past few years.

While average global rainfall is predicted to increase under global warming, not every point on the planet would experience greater rainfall. Evaporation and precipitation occur at different places, and while wet regions could receive even more rainfall if the planet warms, drier regions may have even more acute shortages of water as evaporation is accelerated in those areas. The Sahel, as mentioned before, has become drier over the past several decades, accelerating desertification and placing an even greater premium on already-stretched water supplies.

As research continues into the effects of global climate change on extreme weather, it is important to consider the human and economic toll of extreme weather events. A potential increase in frequency or intensity of these events is another strong reason why we must take action to counteract global climate change.

Changes in climate could exacerbate periodic and chronic shortfalls of water, particularly in arid and semi-arid areas of the world. Developing countries are highly vulnerable to climate change because many are located in arid and semi-arid regions, and most derive their water resources from single-point systems such as bore holes or isolated reservoirs. These systems, by their nature, are vulnerable because there is no redundancy in the system to provide resources, should the primary supply fail. Also, given the limited technical, financial, and management resources possessed by developing countries, adjusting to shortages and/or implementing adaptation measures will impose a heavy burden on their national economies. There is evidence that flooding is likely to become a larger problem in many temperate and humid regions, requiring adaptations not only to droughts and chronic water shortages but also to floods and associated damages, raising concerns about dam and levee failures (The Regional impacts of Climate change, Intergovernmental Panel on Climate change).

In the following paragraphs, we will have a look at the possibility of slowing down or actually reversing the impact of the enhanced greenhouse effect, i.e. man's influence on the natural climatic cycles.

2.10 Can the enhanced greenhouse effect be reversed or slowed down?

The possible alarming effect of human influence on natural climatic cycles has been highlighted throughout the literature review of this study. The purpose of this chapter is to briefly highlight some of the general procedures and initiatives to slow down or even reverse the effect that human activity induced on climate change.

The enhanced greenhouse effect can be slowed down by following two guideline processes: Increase sinks or decrease sources of greenhouse gases. A sink is a process which removes greenhouse gases from the atmosphere. For example, growing a tree where one did not previously exist, provides a sink for carbon dioxide, because the tree "extracts" carbon dioxide for photosynthesis. A source is a place or activity from which greenhouse gases are emitted. This can be a process such as coal burning or a location such as cultivated fields (SA Weather bureau, 2005).

There are various campaigns throughout the world to reverse or slow down the enhanced greenhouse effect. The success of these initiatives will have to be monitored over a very long period of time though.

In light of the above, over a decade ago, most countries joined an international treaty - the United Nations Framework Convention on Climate Change – to begin to consider what can be done to reduce global warming and to cope with whatever temperature increases are inevitable. In 1997, governments agreed to an addition to the treaty, called the Kyoto Protocol, which has more powerful, and legally binding, measures (United Nations Framework convention on climate change, 2005).

An agreement was made to set targets for reductions of industrialized countries' emissions of greenhouse gases. It requires that industrialized countries as a group reduce their emissions of six greenhouse gases (carbon dioxide - CO_2, methane – CH_4, nitrous oxide – N_2O, hydroflourocarbons – HFC's, perfluorocarbons – PFC's, and sulfur hexafluoride – SF_6) by about 5% compared to 1990 levels in the period 2008–2012 (United Nations Framework convention on climate change, 2005). This means that states that have agreed to its terms and then fail to live up to their commitments will be sanctioned – including by having to reduce their emissions even more in a subsequent period. States that withdraw from the entire agreement cannot however be sanctioned.

The 5% reduction in emissions required by the Protocol is an average: some countries are required to reduce more, and others less. The quotas and targets assigned to each country were arrived at through many rounds of tough negotiations. Figure 2.10.1 (United Nations Framework convention on climate change, 2005) show how different countries must reduce their emissions compared with 1990. Only the three countries, Island, Australia, and Norway, are allowed to increase their emissions relative to 1990 levels by 10%, 8%, and 1%, respectively. Russia, Ukraine and New Zealand may keep their emissions at the same level as in 1990. The rest of the industrialized countries are to reduce their emissions 6–8% from 1990 levels in the period 2008–2012.

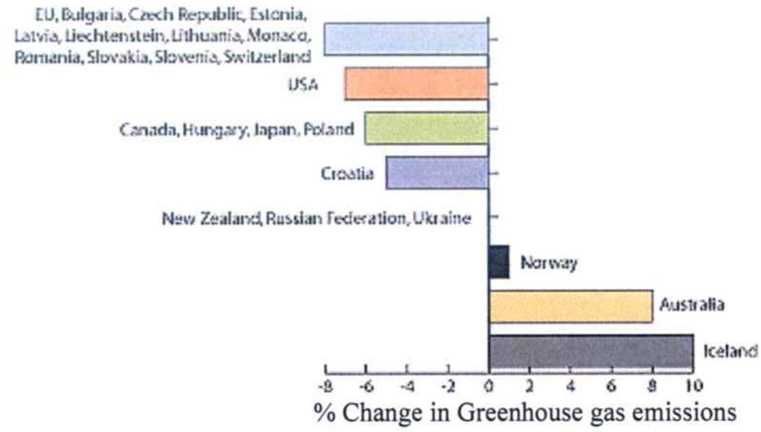


Figure 2.10.1: Kyoto protocol targets for industrialized countries

The Convention on Climate Change set an overall framework for inter-governmental efforts to tackle the challenges posed by climate change. It recognized that the climate system is a shared resource, whose stability can be affected by industrial and other emissions of carbon dioxide and other heat-trapping gases. The 1997 Kyoto Protocol, shares the Convention's objective, principles and institutions, but significantly strengthens the Convention by committing parties to individual, legally-binding targets to limit or reduce their greenhouse gas emissions.

The status of ratification of various countries of the Kyoto protocol as on 29 April 2005 can be found in Appendix A of this report (United Nations Framework convention on climate change, 2005). The Kyoto Protocol took effect on 16 February 2005.

This study strives to investigate the effect of climate change on rainfall intensities, with the case study specifically looking at the Cape Town city bowl. The effect of slowing down or reversing the enhanced greenhouse effect induced by human activity, were not taken into account in this study, but the importance of such initiatives cannot be over-emphasized. In the next chapter, we will have a look at climate change models in general, with the detailed case study following in Chapter 4.

3. Climate change models

As discussed in previous chapters, the climate system is extremely complex. Consequently, there is no simple way of determining how much the climate will change in response to rising greenhouse gas levels. Complex computer simulations are therefore essential for understanding climate change (Climate change information kit, 1999).

Computers allow scientists to model the many interactions between different components of the climate system. The most detailed projections are based on coupled atmosphere-ocean general circulation models (AOGCM's). These are similar to the models used to predict the weather, in which physical laws governing the motion of the atmosphere are reduced to sets of equations to be solved by supercomputers. However, climate models must also include equations representing the behaviour of oceans, land vegetation, and the cryosphere (sea ice, glaciers and ice caps).

Changes in cloud cover and ocean currents may either amplify or reduce the response. Models generally predict that percentage cloud-cover will change in a warmer world, but depending on the type and location of the clouds, this could have various effects. Clouds reflect sunlight, implying that more clouds will have a cooling effect. But most clouds, particularly those at high altitudes, also have an insulating effect: being very cold, they shed energy to space relatively ineffectively, thus helping to keep the planet warm. So the net cloud feedback could go either way. Clouds are the main reason for the large uncertainty about the size of warming under any given emissions scenario (Climate change information kit, 1999).

The speed and timing of climate change also strongly depends on how the oceans respond. The uppermost layers of the oceans constantly interact with the atmosphere and are expected to warm together with the earth's surface. It however takes over 40 times as much energy to warm the top 100m of the ocean as to warm the entire atmosphere by the same amount (Climate change information kit, 1999). With ocean depths reaching several kilometers, the oceans will therefore slow down any atmospheric warming. How much they slow it down, depends on how deep the warming penetrates. Although major improvements have been made in modeling some ocean processes, the exchange of heat between the atmosphere and ocean depths remains an important source of uncertainty (Climate change information kit, 1999).

Confidence in the ability of models to project future climate is however growing (Climate change information kit, 1999). The representation of many processes, such as water vapour and the horizontal transport of heat in the oceans, has improved. Climate models provide credible simulations of climate, at least down to sub-continental scales, and even at smaller scales. They have been able to reproduce, for example, the 20th century's warming trends, as well as some aspects of ancient climates. As a result of these improvements, several climate models have now been run successfully without the need for non-physical adjustments to keep their climates stable. There are however significant uncertainties regarding clouds and their interaction with radiation and aerosols (Climate change information kit, 1999).

It must be remembered that climate models are scientific tools, not crystal balls. Large climate modeling experiments consume enormous computing resources and are so expensive that each year only a handful of such experiments can be performed world-wide (Climate change information kit, 1999). Even the most sophisticated models are approximate representations of a very complex system, so they will never be an infallible guide to the future. We can think of climate models as sophisticated tools for extending our knowledge of present and past climate into an unexplored future.

It must be emphasized, that it is not the aim of this study to verify the predicted values of the climate models. The results of three climate change models will be analyzed, and compared to historical data. From this comparison, the best-fit model was chosen and used for comparing the probable future rainfall scenario for the study area, with the known historical rainfall, measured at the Molteno station. The three models that will be used in this study are Echam, Csiro and Hadam. All three models will be analyzed, and the control data (refer chapter 4 for detail) for all models will be visually and statistically compared to the historical data to obtain the most suitable model for this specific application.

The Csiro model was developed by The Commonwealth Scientific and Industrial Research Organisation (CSAG, 2005). This is an Australian centre that has various climate research projects, including those of climate modeling.

Echam was developed at the Max Plank Institute for Meteorology (MPI-Met), in Hamburg Germany (CSAG, 2005). MPI-Met is one of the world's leading climate research institutions. Models used at the MPI cover atmosphere, ocean, land, and include physical, chemical, as well as biological aspects. Models are developed for global and for regional applications.

Hadam originates from the Hadley Centre for climate prediction and research (CSAG, 2005). This centre provides a focus, in the United Kingdom, for the scientific issues associated with climate change. Simple models of the climate system have been developed and used both to gain physical insight into major features of the behaviour of the climate system, and to produce climate projections for a range of assumptions about emissions of carbon dioxide and other greenhouse gases.

Atmosphere general circulation models, (AGCMs), consist of a three-dimensional representation of the atmosphere coupled to the land surface and cryosphere. An AGCM is similar to a model used for numerical weather prediction (weather forecasting), but because it has to produce projections for decades or centuries rather than days it uses a coarser level of detail. The AGCM has to be provided with data for sea surface temperatures and sea-ice coverage. Hence an AGCM by itself cannot be used for climate prediction, because it cannot indicate how conditions over the ocean will change. AGCMs are useful for studying atmospheric processes, the variability of climate and its response to changes in sea-surface temperature.

An Ocean general circulation model (OGCM) is the ocean counterpart of an AGCM; it is a three-dimensional representation of the ocean and sea-ice. OGCMs are useful by themselves for studying ocean circulation, interior processes and variability, but they depend on being supplied with data about surface air temperature and other atmospheric properties.

Coupled atmosphere-ocean general circulation models (AOGCMs) are the most complex models in use, consisting of an AGCM coupled to an OGCM. Some recent models include the biosphere, carbon cycle and atmospheric chemistry as well. AOGCMs can be used for the prediction and rate of change of future climate. They are also used to study the variability and physical processes of the coupled climate system. Climate projections from the Hadley centre make use of the Hadam model, which is an AOGCM.

The general principle used for all these models, is to compare the relationship between any station's historical data, with a global gridded data set, as developed by NCEP (The National Centers for Environmental Prediction). This gridded data set is a data set that incorporates numerous records, in order to produce a global analysis of more than 50 years of data. The information is grouped together, and a gridded data set is produced. The relationship between any station's specific data, and the NCEP gridded data, are used to "calibrate" any climate change model, in order to ensure that this unique relationship will be preserved when any climate predictions are made. The climate change model is then used to simulate the climate for a period from say 1900 to 2100. The historical data for the period before the 1970's are generally not used by climate systems analyzers, as it usually contains too much patched data as well as data that is perceived to be inaccurate as a result of measuring irregularities. The models' simulated data for the period ±1970's to 2000 (the period corresponding to the historical period with data that is accepted to be more accurate or credible as per the above explanation with respect to earlier measuring inaccuracies) are called **control data**, as this data can be used to verify the models' accuracy by comparing it to the known historical data. The models' simulated data for any period in the future is called **predicted- or future data** (CSAG, 2005). Figure 3.1, graphically explains the concept.

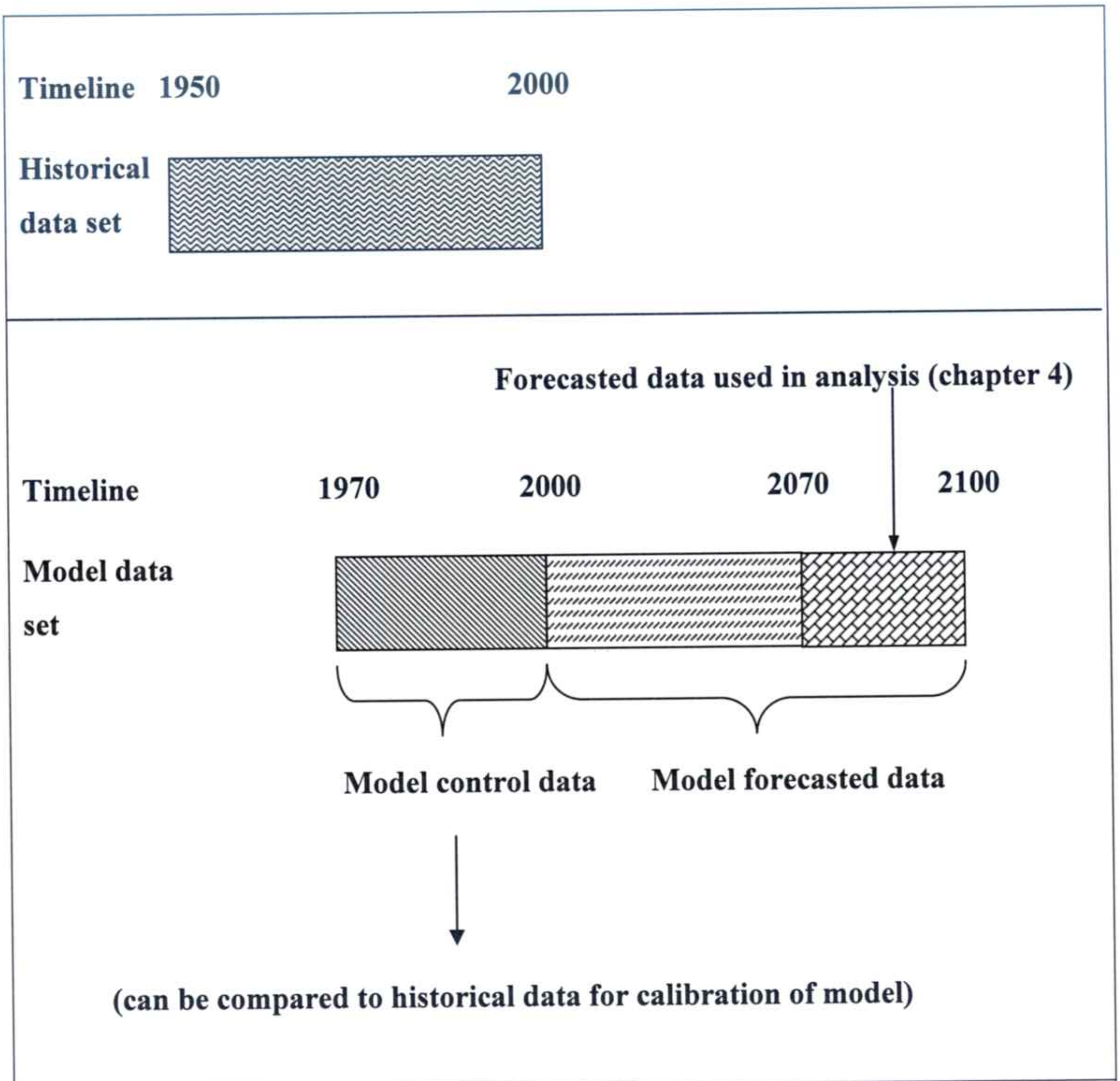


Figure 3.1: Relationship between model data and historical data

With this general knowledge of climate change models as well as the earlier introductory discussion of various possible impacts that climate change might have in the future, we will now have a look at the detailed case study.

4. The influence of climate change on the intensity of rainfall in the City of Cape Town – A case study

4.1 Comparison of historical data with forecasted data for Molteno station, for less than 24 hour storm duration

Historical rainfall data[2], for a 46 year period – 1956 to 2002 – has been obtained from the Climate Systems Analysis Group (CSAG) at the University of Cape Town (UCT) for the study area as shown in Figures 4.1.1a, and 4.1.1b. The 24 hour rainfall data was used to determine sub-daily intensities for the entire data set. The study was performed for these shorter-period intensities, because the average design storm durations for the study area (equal to the time of concentration) were assumed to be of an order of magnitude of less than 24 hours.

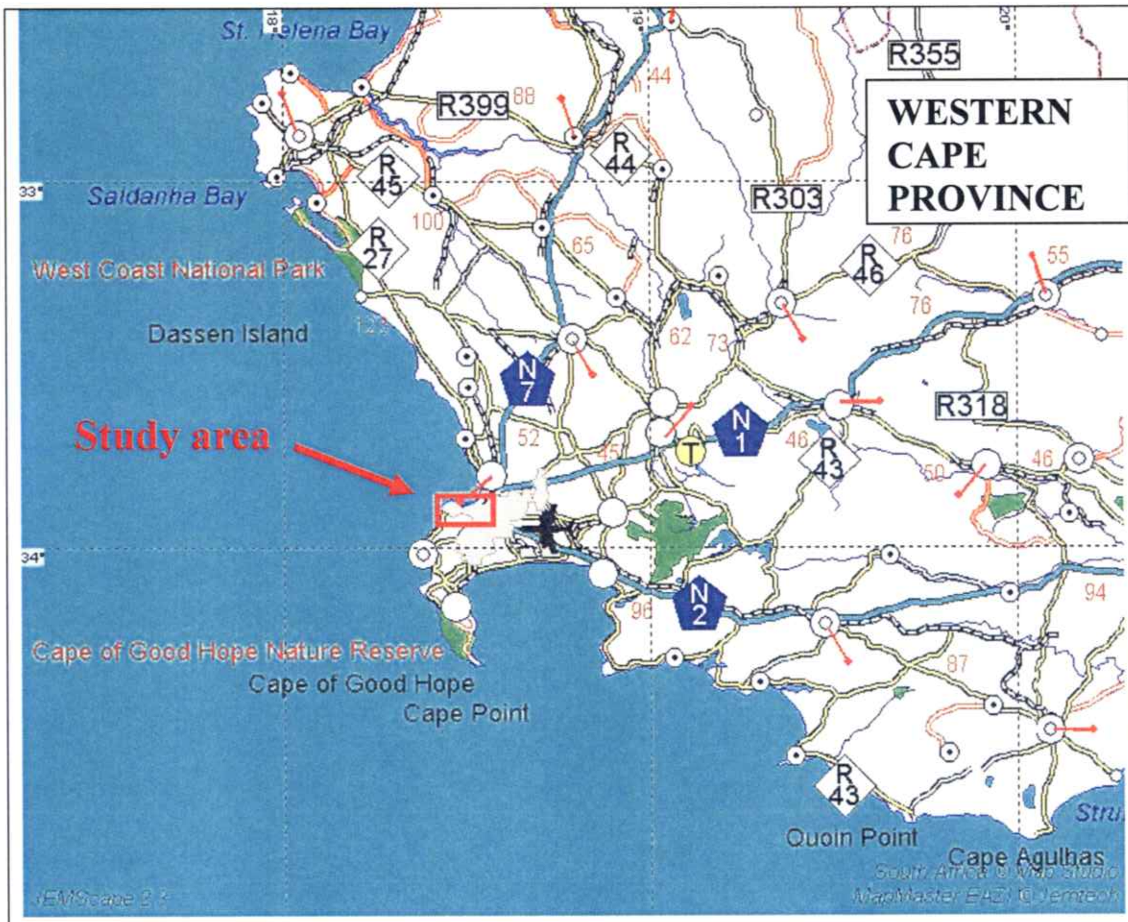


Figure 4.1.1a: Study area: The City of Cape Town (City Bowl) in the Western Cape

[2] Information originally obtained from the City of Cape Town – Molteno Reservoir – Data set 1956 to 2002

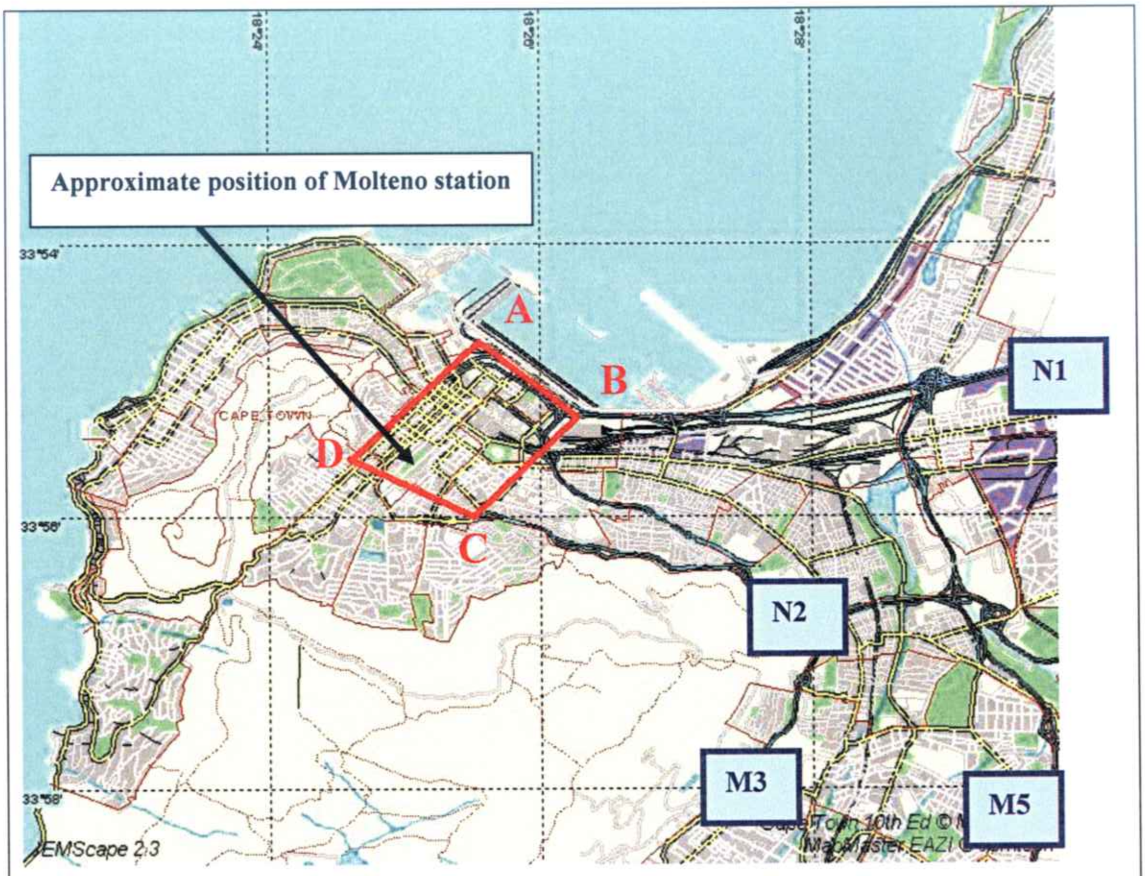


Figure 4.1.1b: Study area: The City of Cape Town – City Bowl

The approximate coordinates (Clark-Lo19 survey system) for the study area, is as follows:

- A – 18^0 25' 40''East and 33^0 55' 0'' South (+5 300 Y ; 3 754 400 X)
- B – 18^0 26' 20''East and 33^0 55' 20'' South (+5 200 Y ; 3 754 900 X)
- C – 18^0 25' 50''East and 33^0 56' 0'' South (+5 280 Y ; 3 756 300 X)
- D – 18^0 25' 0''East and 33^0 55' 40'' South (+5 400 Y ; 3 755 600 X)

The result of the numerical analysis can be found in Appendices B and C of this report. Adamson (1981) determined the ratio of various sub-24 hour rainfall volumes to 24 hour rainfall volumes, refer Table 4.1.1. According to Alexander (1990 – from Hydrology 414 Class notes), the area reduction factor, for sub-catchments smaller than $10km^2$ (as is the case for the study area's sub-catchments) and storm-duration less than or equal to 1 hour, must be taken as 1, that is, the area rainfall can be assumed to be equal to the point rainfall. The area reduction factor for this study catchment area was therefore taken as one.

Daily rainfall volumes for the Molteno reservoir (station number 0020746) were multiplied with 1.11, to obtain 24 hour rainfall. This was done to make provision for the "clock-factor.[3]" The 24-hour rainfall values were then multiplied by the Adamson factors, to obtain shorter duration rainfall intensities. Adamson ratios were originally obtained from analysis of historical data. As this study strives to determine whether rainfall intensities could change (as a result of the enhanced greenhouse effect), it is not sensible to use Adamson's ratios to obtain sub-24 hour rainfall values from forecasted 24-hour rainfall values. For the purpose of this study, the Adamson ratios were however used, to attempt to compare historical- and forecasted data.

Table 4.1.1: Ratio of D (hour) storm depth to 24 hour storm depth of same probability of occurrence (Adamson, 1981).

D (hours)	Winter rainfall / coastal zone factors
0.1	0.14
0.25	0.23
0.5	0.32
1	0.41
2	0.53
3	0.60
4	0.67
5	0.71
6	0.75
8	0.81
10	0.85
12	0.89
18	0.96
24	1.00

These values were compared with the intensities as determined with the IDF-equations of Stephenson and Op ten Noort[4], as well as intensity-duration-frequency (IDF) curves, obtained from the City of Cape Town (Du Plessis, 1992). It was found that the Stephenson and Op ten Noort equation yields larger values for the same return

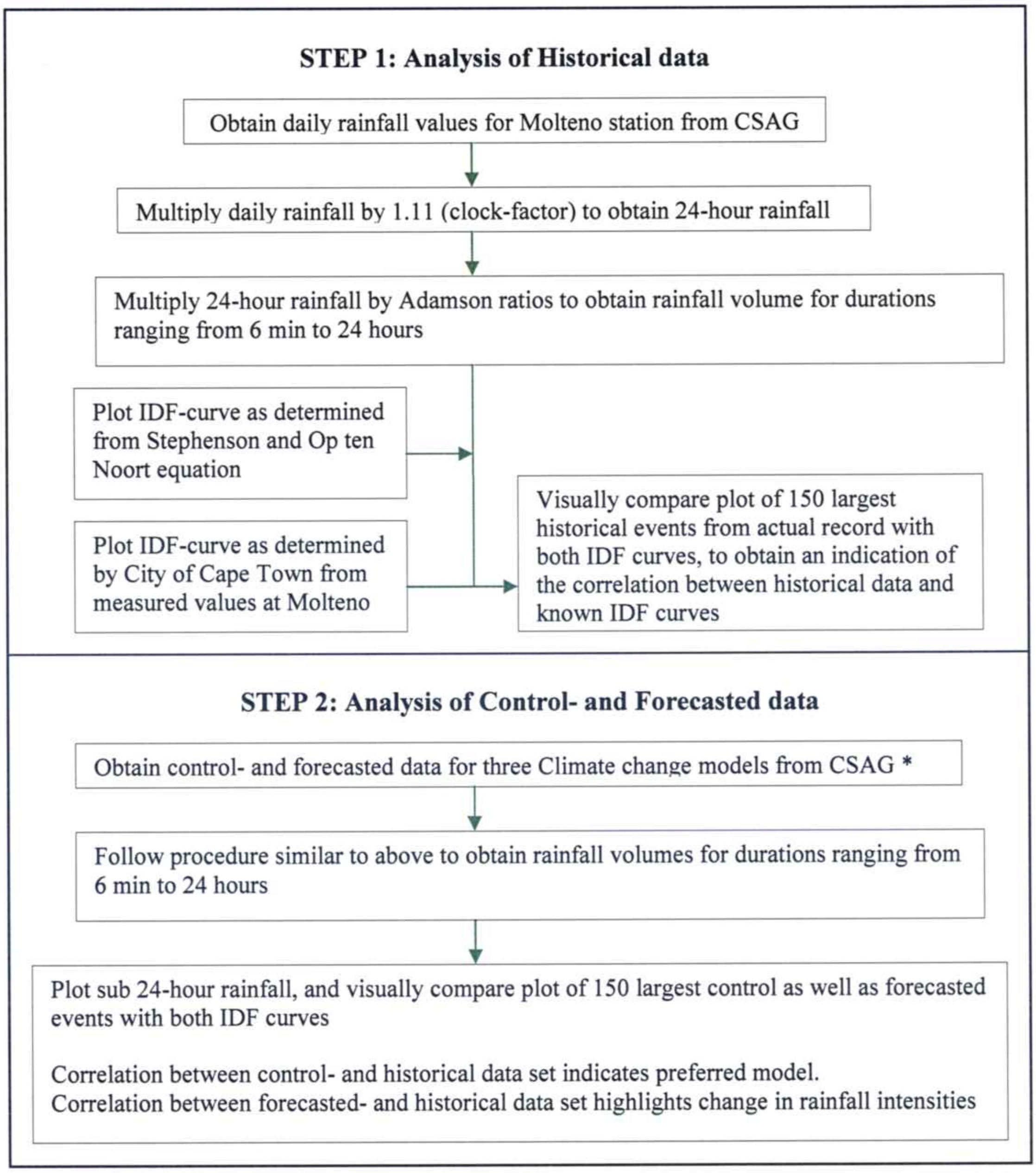
[3] Daily rainfall measured from 8:00 to 7:59 the following morning. The peak 24-hour rainfall could however be between (say) 10:00 and 9:59 the following day. To make provision for this, the daily rainfall are usually multiplied by a clock factor.

[4] $I = (3.4 + 0.023 * MAP) * T^{0.3} / (0.2 + t_d)^{0.75}$, with MAP = mean annual precipitation = 700mm, T = recurrence interval and t_d = storm duration.

period and storm duration than the IDF curves from City of Cape Town. The City of Cape Town curves were determined from measured 5 minute duration rainfall depths, and can therefore be seen as an actual representation of the study area.

Detail of the calculation procedure, can be found in Flowchart 4.1.1. The methodology is also explained in the paragraphs following Flowchart 4.1.1.

Flowchart 4.1.1: Methodology followed in analysis where sub 24-hour historical- and forecasted data for Molteno station was compared



* Models used were Echam, Hadam and Csiro. Refer chapter 3 for detail on models as well as significance of control- and forecasted data

An extract of the historical data set for Molteno station was also obtained from CSAG. The extract data set was for the period from 1979 to 2000. This data set was used as input for the climate change model, because of possible irregularities in the longer historical data set (Walawege, 2005). In addition to the historical data set and the extract thereof, predicted 24 hour rainfall volumes for the Molteno station (for the years 2070 to 2100) as well as control sets of data, were received, for three different climate change models. As mentioned in chapter 3, the three models used in this study are Csiro, Echam and Hadam. The control data set is used to verify which climate change model yields the best / most comparable – and therefore most probable – future results. Intensity-depth-duration curves were determined for all of the above data sets (two historical data sets, three control data sets as well as the three future data sets). In all these cases the Adamson ratios were used to determine the shorter duration rainfall depths.

The extract of the historical data set was compared to the longer historical data set to verify whether the two data sets demonstrate the same trends, as far as peak events are concerned. It was found that for the historical data set as well as the extract (24 hour rainfall), the largest recorded event was in the order of a 1:50 year recurrence interval event (2% probability) when compared to the Du Plessis curves. It is interesting to note that the same event would be of the order of 1:20 years according to the Stephenson and Op ten Noort equation. As mentioned before, the Du Plessis curves are considered to be a better representation of the rainfall at the study area, it being derived from measured rainfall depths, and not based on large-scale area averages as is the case in the Stephenson and Op ten Noort equation. Figure 4.1.2 shows the IDF curves of Stephenson and Op ten Noort as well as Du Plessis and the points from the actual data at Molteno, for the 46 year historical period. Details of the other curves can be found in Appendix B of this report.

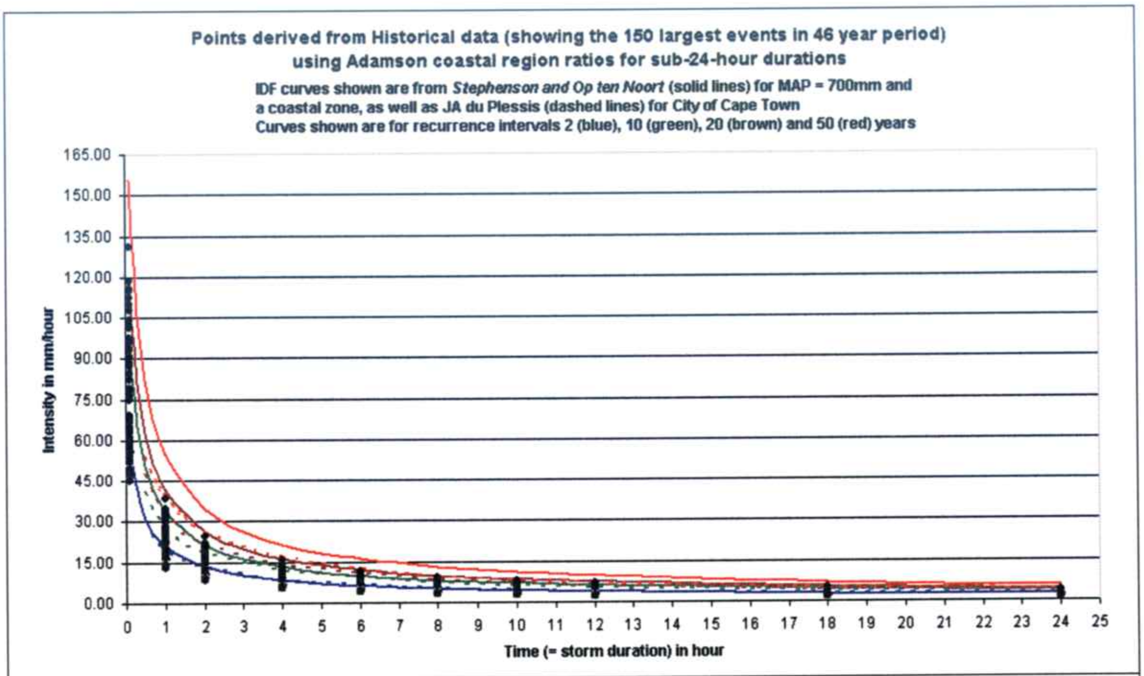


Figure 4.1.2: IDF curves from Stephenson and Op ten Noort and Du Plessis, as well as points plotted from 46 year historical period at Molteno

The three control sets were then analyzed and visually compared to the historical data sets, to verify which climate change models yields the most acceptable and probable results, refer Appendix B of this report for details. It was found that Csiro's results does not compare very favourably with the historical data. Both Echam and Hadam's results compares reasonably well with the historical data sets. On the basis of the comparison of the control- and the historical data sets, it was decided to compare the predicted future results from the Echam model with the historical data set. As mentioned earlier, the model's predicted 24-hour rainfall was multiplied by the Adamson factors, to determine the shorter duration rainfall depths. See Appendix B of this report for details. Figure 4.1.3 shows the predicted future rainfall IDF points, as compared with the actual Du Plessis curves, as well as the Stephenson and Op ten Noort curve as equated from historical data.

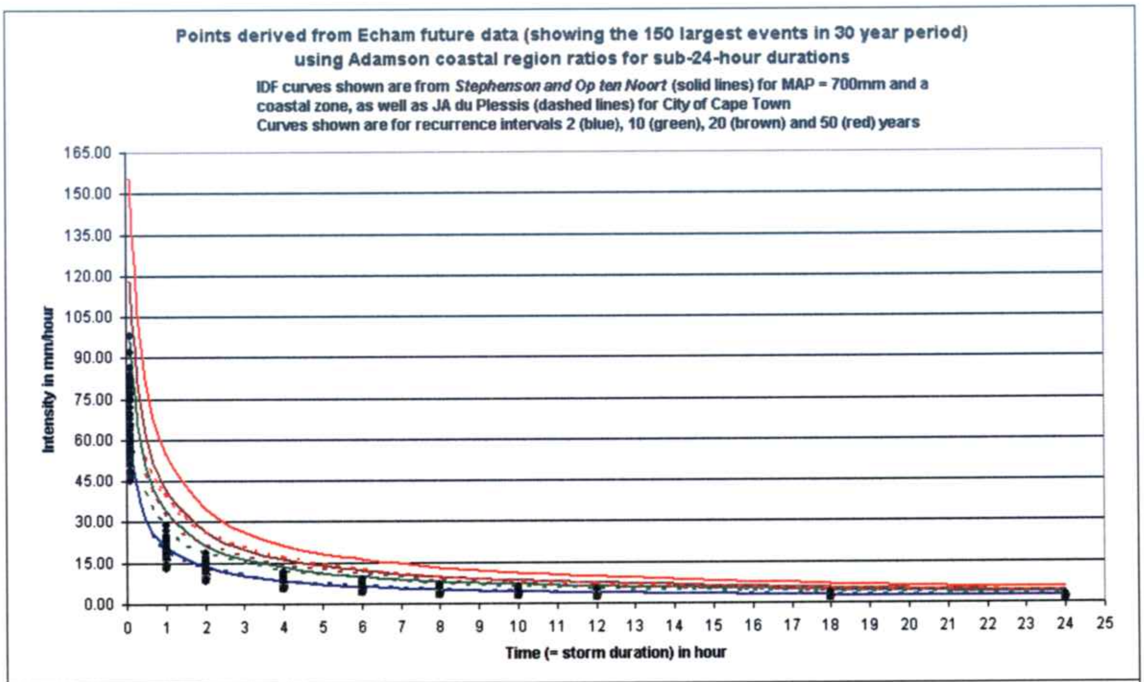


Figure 4.1.3: IDF curves from Stephenson and Op ten Noort and Du Plessis, as well as points plotted from Echam model for predicted future rainfall

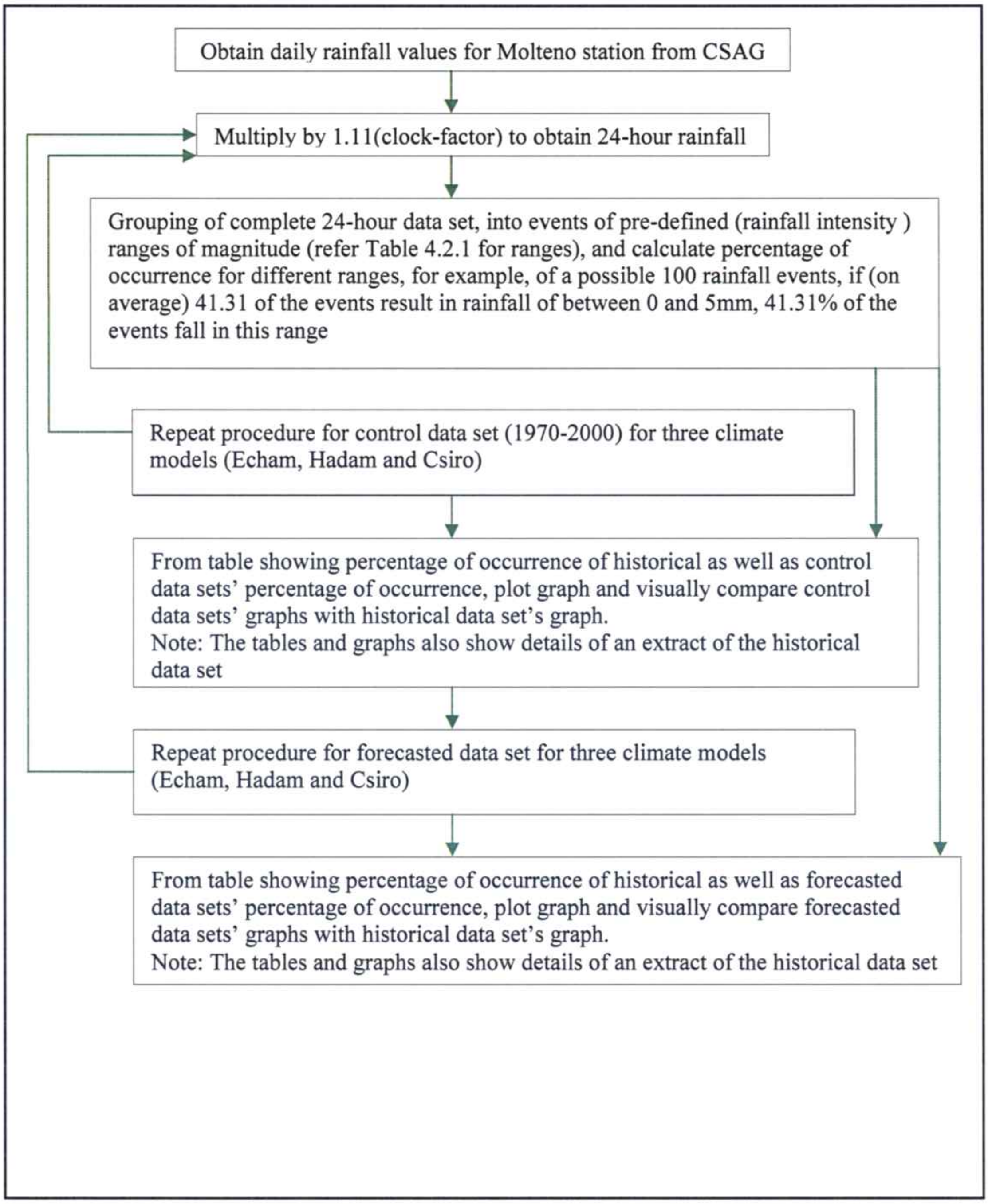
The surprising result was that according to the Echam model, the largest predicted event in the 30 year period would only be of an order of magnitude equal to about 1:10 years, when compared to Du Plessis curves, refer Appendix B for details. Statistically we would however expect that the largest event in a 30 year period should be the 1:30 year storm. It is also generally expected that the intensity of rainfall events should in fact increase as a result of the enhanced greenhouse effect (at the study area), with longer spells of non-occurrence between rainfall events.

As mentioned earlier, the use of Adamson ratios on predicted future events are erroneous. It is indeed expected that rainfall patterns will change, so the use of ratios of shorter duration storms to 24-hour storms, as derived from historical data, to determine shorter duration rainfall depths for the future, cannot be correct. In light of the above, it was decided to analyze the data as described in paragraph 4.2, in order to be able to omit the use of the Adamson ratios.

4.2 Comparison of historical data with forecasted data for Molteno station, for 24 hour storm duration

Flowchart 4.2.1, explains the calculation procedure followed during further analysis. The methodology is also briefly explained in the paragraphs following Flowchart 4.2.1.

Flowchart 4.2.1: Methodology followed in percentage of occurrence of different size 24-hour events-analysis (applicable to Molteno station only)



It was decided to determine the percentage occurrence of each rainfall event, on the basis of the events' 24-hour rainfall depth. The rainfall events of any given data set was grouped together in events of different rainfall depth ranges for 24-hour rainfall, as shown in Table 4.2.1. The number of events in each range was then expressed as a percentage of occurrence, relative to the total number of rainfall events for the given data set. In this way, the different lengths of the various data sets does not really matter, as the percentage of occurrence of an event for the given range is compared, and not the actual number of events (for the given range) in any data set. It is however important to analyze a not to short data set, as this might implicitly exclude large recurrence interval events. It was decided that the longer historical data set's length of 46 years (1956 – 2002), as well as the forecasted future data set's length of 30 (2070 – 2100) years should included events of acceptably large recurrence intervals, considering that, for peak floods, design recurrence intervals for internal stormwater systems are typically in the order of 1:2 to 1:10 years.

Table 4.2.1: Table of percentage of occurrence of different rainfall depth ranges of 24-hour rainfall events: Historical and **Control** data

Different rainfall ranges	**Historical data set (1956 – 2002)**	**Extract of historical data set (1979 – 2000)**		**Model control data (Model output for period 1970 – 2000)**					
				Csiro control		**Echam control**		**Hadam control**	
	Actual %	Actual %	Relative %*	Actual %	Relative %	Actual %	Relative %	Actual %	Relative %
0-5mm range	41.31	41.69	1.01	41.96	1.02	39.75	0.96	38.32	0.93
5-10mm range	24.62	21.92	0.89	20.50	0.83	21.00	0.85	22.38	0.91
10-15mm range	15.25	12.44	0.82	13.93	0.91	14.18	0.93	13.96	0.92
15-20mm range	7.37	9.07	1.23	9.19	1.25	8.83	1.20	9.36	1.27
20-25mm range	4.28	4.19	0.98	4.29	1.00	5.09	1.19	3.95	0.92
25-30mm range	2.31	3.43	1.48	3.23	1.40	3.44	1.49	3.95	1.71
30-35mm range	1.89	2.38	1.26	2.77	1.47	2.58	1.37	3.40	1.80
35-40mm range	1.10	1.45	1.32	1.18	1.07	1.38	1.25	1.59	1.45
40-45mm range	0.62	1.51	2.44	1.42	2.29	1.57	2.53	1.35	2.18
45-50mm range	0.31	0.29	0.94	0.41	1.32	0.64	2.06	0.45	1.45
>50mm range	0.96	1.63	1.70	1.04	1.08	1.53	1.59	1.28	1.33
Percentage	**100**	**100**	-	**100**	-	**100**	-	**100**	-

* Value of actual percentage divided by corresponding percentage in Long historical data set column.

Figure 4.2.1, is a graphical representation of Table 4.2.1. It can be seen that the long historical data set as well as the extract compare reasonably well. The control data sets all compare reasonably well to the historical data set, with the Hadam- and Csiro models possibly showing the worst correlation, and the Echam model showing reasonable results. It was however decided to analyze all three climate change models' forecasted rainfall data in this way, to be able to compare all three these models to the two historical data sets, particularly in light of the fact that no model showed a very good correlation.

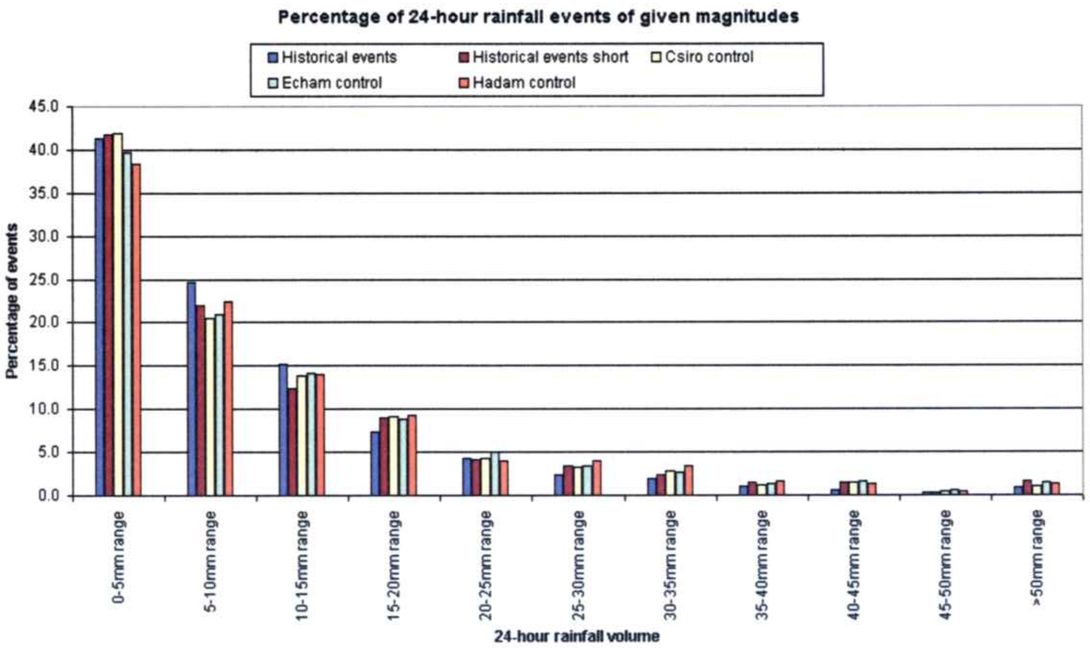


Figure 4.2.1: Percentage of occurrence of different recurrence interval storms for all historical rainfall events, as well as control data sets of climate change models

As mentioned, climate change models were then used to analyze the same data-set[5], and to forecast possible daily rainfall volumes for the study area. This data were then multiplied by 1.11 (the clock-factor, as explained earlier) to obtain 24-hour rainfall volumes, and the percentage of occurrence was once again determined as explained before.

[5] It must be noted that the validity of the climate change models are not being questioned in this study, but the rainfall that is forecasted by these models are simply analyzed and the resulting rainfall depths are then compared to rainfall depths derived from the historical data.

Table 4.2.2 and Figure 4.2.2 shows the results of the analysis of the three models' forecasted rainfall data, as well as the historical data set and the extracted historical data set's, analysis. It can be seen that the Echam model, the preferred model according to the analysis of the control data set, forecasts a reduction in the percentage of occurrence for smaller events (0 to 10mm range), when compared to the historical data set. If the percentage of occurrence for forecasted data for small 24-hour rainfall events (0 to 10mm range) decrease compared to the percentage of occurrence of historical data of the same range, it follows that the larger events' percentage of occurrence must increase, when compared to the historical data.

Table 4.2.2: Table of percentage of occurrence of different ranges of 24-hour rainfall events: Historical and **Forecasted** data

Different rainfall ranges	**Historical data set (1956 – 2002)**	**Extract of historical data set (1979 – 2000)**		**Model forecasted data (Model output for period 2070 – 2100)**					
				Csiro future		**Echam future ****		**Hadam future**	
		Actual %	Relative % *	Actual %	Relative %	Actual %	Relative %	Actual %	Relative %
0-5mm range	41.31	41.69	1.01	43.51	1.05	39.95	0.97	38.88	0.94
5-10mm range	24.62	21.92	0.89	19.65	0.80	21.05	0.85	23.22	0.94
10-15mm range	15.25	12.44	0.82	14.39	0.94	13.24	0.87	13.11	0.86
15-20mm range	7.37	9.07	1.23	9.20	1.25	9.86	1.34	9.06	1.23
20-25mm range	4.28	4.19	0.98	3.81	0.89	4.56	1.07	4.37	1.02
25-30mm range	2.31	3.43	1.48	3.22	1.39	4.24	1.84	3.71	1.61
30-35mm range	1.89	2.38	1.26	2.32	1.23	3.22	1.70	2.97	1.57
35-40mm range	1.10	1.45	1.32	0.90	0.82	1.26	1.15	1.44	1.31
40-45mm range	0.62	1.51	2.44	1.85	2.98	1.34	2.16	1.41	2.27
45-50mm range	0.31	0.29	0.94	0.39	1.26	0.43	1.39	0.51	1.65
>50mm range	0.96	1.63	1.70	0.75	0.78	0.86	0.90	1.33	1.39
Percentage	**100**	**100**	-	**100**	-	**100**	-	**100**	-

* Value of actual percentage divided by corresponding percentage in Long historical data set column.

** Echam was the preferred model according to the comparison of the control- and the historical data sets. It was however decided to show the results of the other two models as well, as explained earlier.

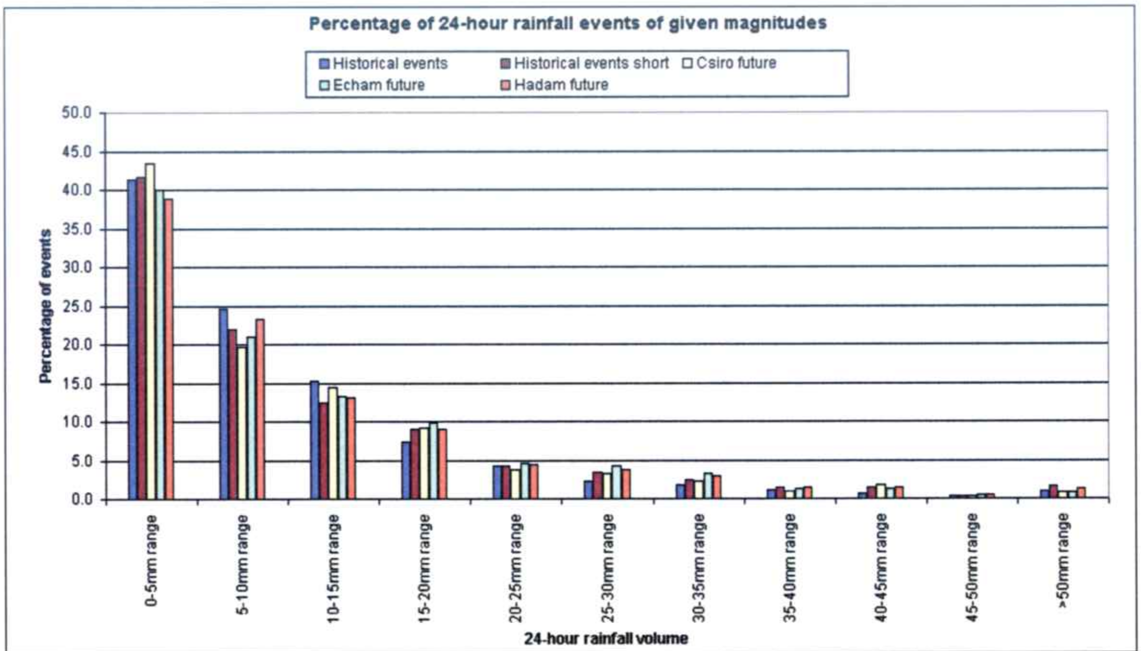


Figure 4.2.2: Percentage of occurrence of different recurrence interval storms for all historical rainfall events, as well as future data sets of climate change models

It is clear from the graph that some rainfall ranges tends to increase (when compared to the historical values), and some tend to decrease. The general tendency is however for an increase in percentage of occurrence for events larger than 15mm per 24 hour.

It must be remembered that this analysis was performed using 24-hour rainfall depths. The conclusion that can be reached from this stations' data, is that the percentage of occurrence of larger rainfall events (all events larger than 10mm of rainfall per 24 hour), could increase as a result of climate change, and that the percentage of occurrence of small rainfall events (of magnitude less than 10mm of rainfall per 24 hour) could decrease. This result is in line with the general expectation of a decrease in the number of events (or small events) and an increase in larger events.

4.3 Comparison of historical data with forecasted data for four additional stations near Molteno station, for 24 hour storm duration

The methodology for the calculation procedure followed for the four additional stations, as well as the combination of all five stations, are briefly highlighted in the following paragraphs.

The 24-hour rainfall depth distribution for four other stations in the vicinity of the study area was also determined. Detail of the four other stations that were investigated, as well as the original Molteno station, can be found in Table 4.3.1. These stations are all close to the original study area, with comparable rainfall producing mechanisms, despite having fairly different mean annual precipitations.

Table 4.3.1: Detail of expanded study area's rainfall stations

Station number	Station name	Mean annual precipitation
0020714	Greenpoint	493mm
0020719	Table Mountain (House)	1690mm
0020748	Table Mountain (St Michaels)	1380mm
0004695	Silvermine nature reserve	1215mm
0020746	Molteno	610-773mm*

* Ranging between 610mm (WB42) and 773mm (WR90) depending on source used. MAP of 700mm used in analysis

Figure 4.3.1 shows the proximity of the 4 additional stations to the Molteno station. All positions shown are approximate.

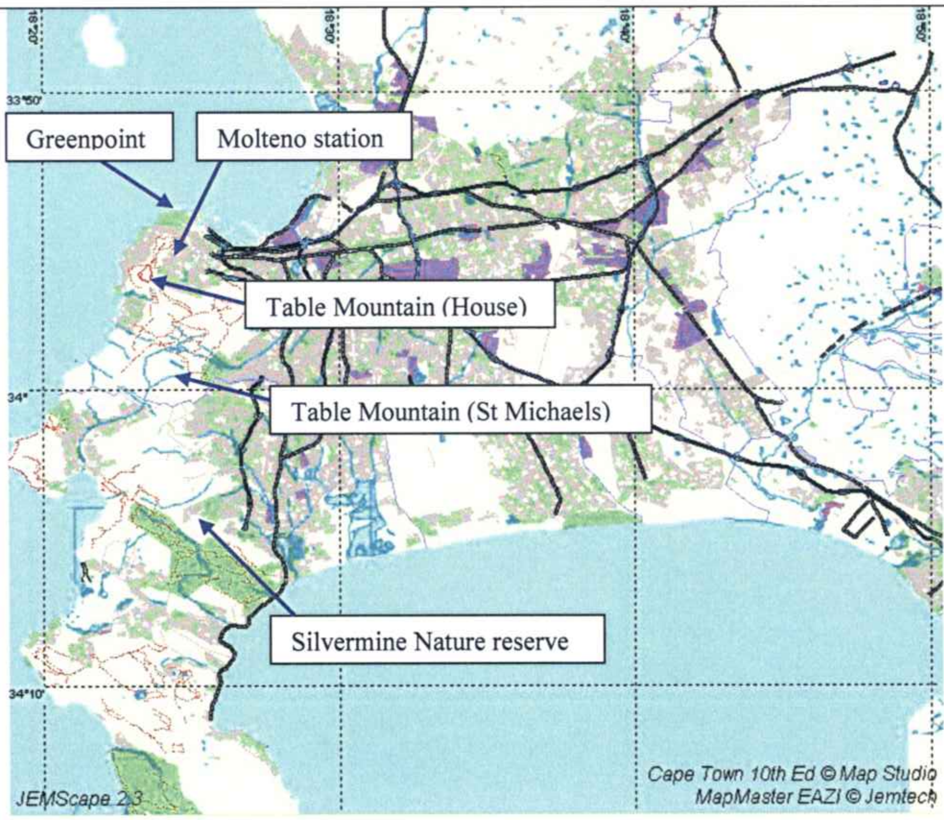


Figure 4.3.1 Expanded study area showing four additional stations

The historical data set for all the rainfall stations, were once again compared to all three models' control data sets, to establish which model should yield the most credible results. Details of the individual results for the four additional stations can be found in Appendix D of this report. Appendix D shows the percentage of occurrence of both the control as well as the forecasted data. In both cases the data has also been divided by the historical data set's percentage of occurrence, therefore showing the normalized data.

The different stations' normalized data was added together and divided by five, to yield regionalized, normalized data. After visually comparing the control data with the historical data at all the stations (refer Appendix D for details), it was found that Csiro's results compare favorably with the historical data for stations 20719, 20748 and 4695. For station 20714, Echam was the preferred model. When these models' results of the forecasted data were compared with the historical data (refer Appendix D for results), the trend at Molteno (of increasing percentage of occurrence of larger 24-hour rainfall events) was repeated at stations 20714 and 20748. Stations 20719 and 4695 displayed a marginal increase in percentage of occurrence of smaller events.

The main reason for expanding the study set was to establish if the apparent trend that was identified at Molteno, would be observed at more rainfall stations. It was therefore decided to group the data together, to establish if a regional trend will be apparent for the study area.

The percentage of occurrence of all the previously stated rainfall ranges were determined for the control as well as future data for all four additional stations, for all three climate change models. The percentage of occurrence of the different 24-hour rainfall ranges for the historical data was also determined for all four additional stations. The value of percentage of occurrence of all control and future data was then divided by the corresponding stations' corresponding historical value of percentage of occurrence. In this way the data could be said to have been normalized.

The result was that for control data, a value of close to one would mean that the control data set corresponds closely to the historical data set, and one would have a strong degree of confidence in the particular model's future predictions for the rainfall station in question. For future data, a value of more than one would indicate an increase in percentage of occurrence for the particular 24-hour rainfall range, for the model in question at any given rainfall station. Conversely, for control data, a value far from one, should warn one that the particular model's output should not be considered as credible. Also, for future data, a value smaller than one would indicate a decrease in the percentage of occurrence of the given 24-hour rainfall range. For these data sets, the historical values will obviously all be one (ie. the data was divided by itself).

In an effort to establish a regionalized average, and thereby minimizing the effect of any station irregularities or preferences, the normalized data was then added for all the different 24-hour rainfall ranges for the historical-, control- and the forecasted data sets. This was done for all five rainfall stations, as well as for all three models (in the case of control- and forecasted data). These added data sets were then divided by five (for five rainfall stations) and the result was one regionalized, normalized data set. The above procedure can be explained by the calculation procedure in Figure 4.3.2.

Step 1: Determine % of occurrence for different rainfall ranges for **historical data sets** of all five stations, independently.

Step 2: Determine % of occurrence for different rainfall ranges for **control data sets** of all five stations, independently.

Step 3: Divide control data, for every % of occurrence, with the corresponding % of occurrence of the station's historical data set (this is performed for every station) => Five normalized control data sets (one for each rainfall station).

Step 4: Add normalized control data set of each station together (for every % of occurrence) and divide by 5 (because of 5 rainfall stations) => One regionalized, normalized control data set

The above calculation procedure was followed for the forecasted data as well, thereby providing one regionalized, normalized **forecasted data set**.

Figure 4.3.2 Detail of procedure followed to obtain regionalized, normalized data sets

The resultant control data set, are summarized in Table 4.3.2 and graphically shown in Figure 4.3.3.

Table 4.3.2: Table of occurrence, relative to history, of different ranges of 24 hour rainfall events for various models, as an average for all stations for **control data**

24-hour rainfall range / Model	Historical data set	Csiro control data set	Echam control data set	Hadam control data set
0-5mm range	1.000	0.995	0.914	0.924
5-10mm range	1.000	0.995	0.996	1.031
10-15mm range	1.000	1.011	1.053	1.036
15-20mm range	1.000	1.034	0.997	1.044
20-25mm range	1.000	1.038	1.136	1.015
25-30mm range	1.000	1.061	1.097	1.043
30-35mm range	1.000	1.025	1.294	1.218
35-40mm range	1.000	0.859	1.215	1.209
40-45mm range	1.000	0.816	0.931	0.837
45-50mm range	1.000	0.879	1.120	1.039
> 50mm range	1.000	0.703	0.897	0.720
Sum of all ranges divided by number of ranges	1.000	0.947	1.059	**1.011**

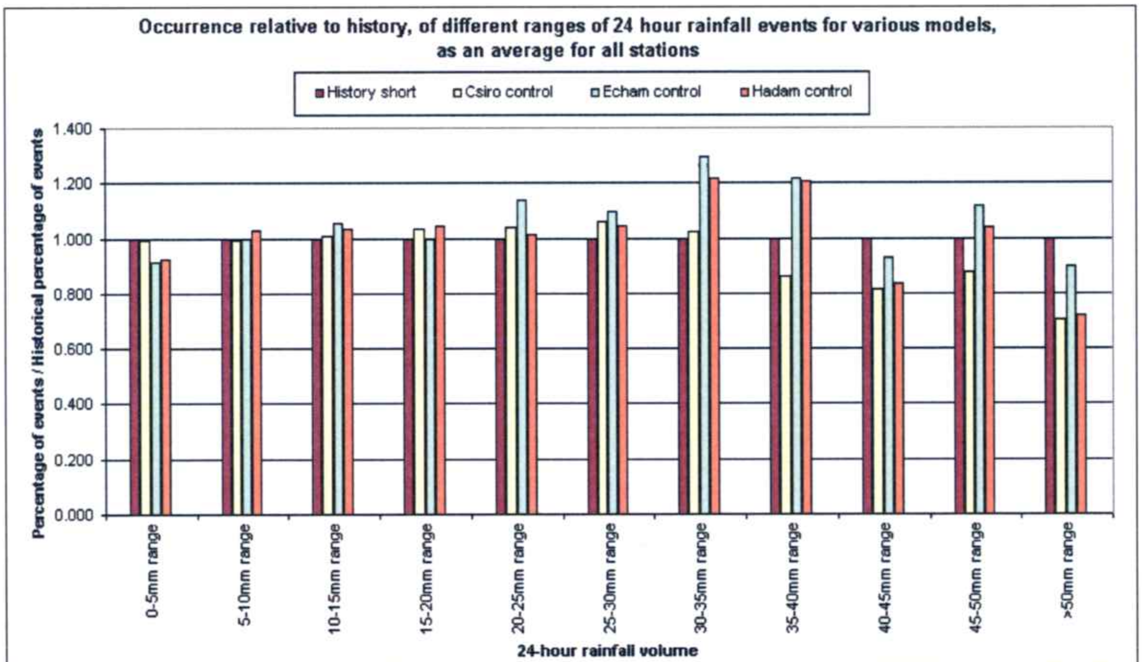


Figure 4.3.3: Figure showing occurrence, relative to history, of different ranges of 24 hour rainfall events for various models, as an average for all stations **for control data**

From Table 4.3.2, it can be seen that, on average, Hadam's results compare most favourably with that of the regionalized and normalized historical data. One would therefore have the most confidence in the predicted future results of this model. As before however, it was decided to show the results of the other models' forecasted data as well, to underline the general trend forecasted by these models.

Table 4.3.3 and Figure 4.3.4, summarizes the results of the regionalized and normalized forecasted data sets.

Table 4.3.3: Table of occurrence, relative to history, of different ranges of 24 hour rainfall events for various models, as an average for all stations for **forecasted data**

24-hour rainfall range / Model	Historical data set	Csiro future data set	Echam future data set	Hadam future data set
0-5mm range	1.000	1.026	0.952	0.955
5-10mm range	1.000	0.983	0.998	1.014
10-15mm range	1.000	1.015	1.051	0.978
15-20mm range	1.000	1.050	1.014	1.002
20-25mm range	1.000	0.975	1.039	1.062
25-30mm range	1.000	0.991	1.157	1.113
30-35mm range	1.000	0.977	1.238	1.115
35-40mm range	1.000	0.831	1.014	1.074
40-45mm range	1.000	0.921	0.851	0.835
45-50mm range	1.000	0.875	1.093	0.961
> 50mm range	1.000	0.588	0.707	0.830

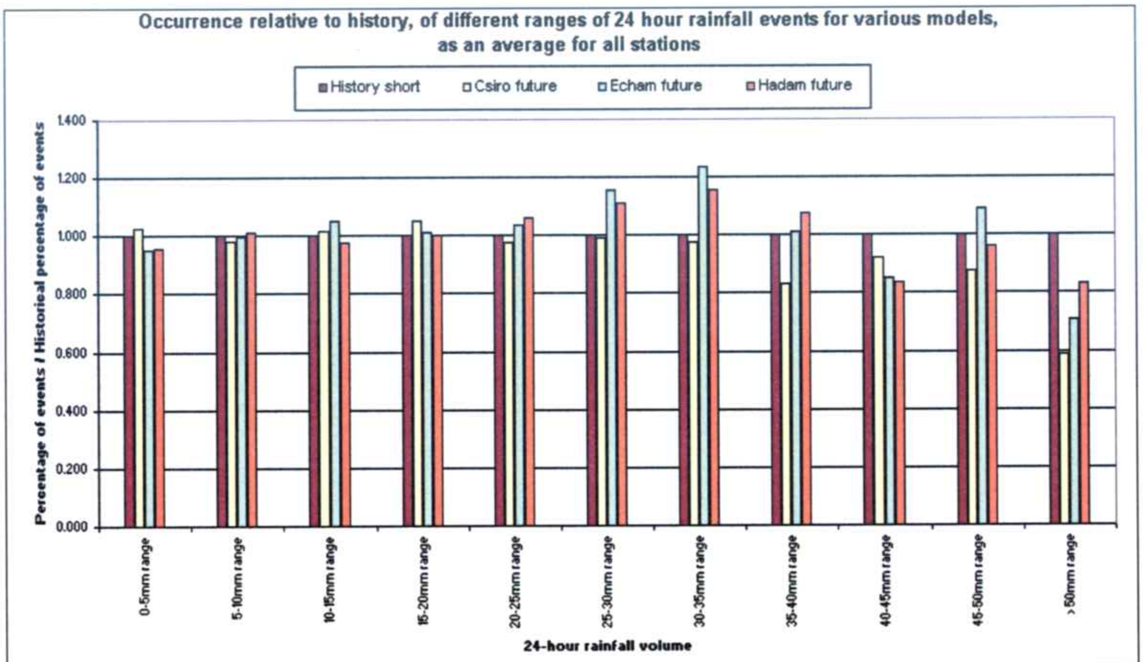


Figure 4.3.4: Figure showing occurrence, relative to history, of different ranges of 24 hour rainfall events for various models, as an average for all stations for **forecasted data**

Unfortunately, a very clear trend could not be seen from the comparison. An apparent increase in the percentage of occurrence was predicted by Echam and Hadam for the 24-hour rainfall range from ± 10mm to ± 40mm. The models seemed to generally predict a decrease in the 24-hour rainfall range above 40mm, apart from the Echam prediction for the 40-45mm range. According to Hadam, the percentage increase in rainfall for the 20-40mm range varies between 6.2% and 11.5%.

4.4 Detailed analysis of all rainstorms at Molteno station, for the period 1958 to 2003

In light of the absence of a clear trend between the rainfall-characteristics and 24-hour rainfall intensities when the historical data was compared to the predicted data, it was decided to investigate the historical data set at Molteno in more detail, analyzing whether a trend could be established in the actual measured short duration rainfall data. The logic was that Molteno has a very long historical data set (in South African terms), with (presumably adequate) measuring dating back to 1956. It was decided to analyze every rainstorm measured at Molteno in detail.

Data as originally retrieved from the autographic rainfall gauge at Molteno by Du Plessis et al (1992) was used in this analsyis. In addition to the data obtained from the above-mentioned study, the data from the gauge at Molteno for the period 1992 to 2003 (actual 5 minute interval readings, as opposed to the 24-hour rainfall used in the preceding analysis) was obtained from the City of Cape Town's Catchment, Stormwater and River Management branch. This data was added to the data from the Du Plessis study, to form one data set, 45 years in length (1958 to 2003). Every rainstorm larger than a pre-determined minimum for different storm lengths was logged. The pre-determined minimums were chosen in accordance with those used in the Du Plessis study and is shown in Table 4.4.1.

Table 4.4.1: Constraints used to select storm events to be used in analysis. Minimum values shown are in millimeter (Du Plessis, 1992)

Duration	**Minutes**								**Hours**				
	5	**10**	**15**	**30**	**45**	**60**	**90**	**120**	**4**	**8**	**12**	**18**	**24**
Minimum	2	3	4	5	6	8	10	12	12	12	12	12	12

A rainfall storm, for example, was checked for time intervals varying from 5 minutes to 24 hours. If 10mm was recorded over 60 minutes, the storm was logged, but if 10mm was recorded over 120 minutes, the storm was left out of the data base used in the analysis (Du Plessis, 1992). In accordance with the earlier study, no clock factor was applied to the data, as real time was used to analyze the data. According to Du Plessis, the difference in readings between the autographic gauge and the 24-hour check gauge did not warrant a general change in the actual rainfall figures. In light of the fact that the data used for the Du Plessis study formed part of the data set used in this study, this principle therefore also had to apply to this study. As explained in Du Plessis (1992), the general tendency found when the autographic gauge's readings was compared to that of the check gauge, was that the actual reading (autographic gauge) tended to be slightly lower than the corresponding check reading. It was argued that since they were mostly interested in the shorter durations, the proportional influence of the difference over a time increment of between 5 and 60 minutes could be considered as insignificant (Du Plessis, 1992). This argument is applicable to the current study as well. It is important to note that for the period from 1991 to 2003 the data obtained were 5 minute readings, and not real-time data. This means that the data was added for 5 minute intervals. The result is that the peak 5 minute data may not have been recorded, and therefore not analyzed. The principle can be explained if we look at the following example.

Example: Assume the following rainfall is recorded (1 minute interval recordings) at a given station:

Time in minutes	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Rainfall depth	2	3	3	8	5	9	2	4	0	0	4	4	2	1	2
5 minute totals	21					15					13				
Rolling total					21	28	27	28	20	15	10	12	10	11	13

If the 5 minute values are simply added, it means that for period 0-5 minutes, 21mm will be recorded. For period 6-10 minutes 15mm will be recorded and for period 11 to 15 minutes 13mm will be recorded. However, if the data had to be added for rolling 5 minute periods, the largest rolling 5 minutes would have been from minute 2 to minute 6, measuring 28mm. This is only critical for the 5 minute storm duration analyzes, as the data were in fact added in rolling periods for storm durations beyond 5 minutes for this study.

The first step in the analyses was to compile a database using the constraints shown in Table 4.4.1. This was done by checking each and every storm using the largest amount of rainfall recorded in that specific time increment. Only one interval was accepted for each storm increment. For example, if a certain 5 minute interval had 3mm of rain, while the following 5 minute interval had 4mm of rain, the 4mm would be logged, and the 3mm would be rejected even though the 3mm is larger than the prescribed minimum. Two 5 minute intervals would only be read on the same day if the storms were deemed to be independent events. This method was originally verified through work done by an independent consultant, and it was found that if the time between independent events was set to be twice the interval length, and subsequently changed to three times the interval length with a maximum of 6 hours between events, no evidence existed that it made any difference to the end results (Du Plessis, 1992).

The database used in the Du Plessis analysis was expanded using the above-mentioned method, to include data from the period 1992 to 2003. It was decided to set a maximum time between so-called independent events, according to the guidelines explained above. The result was that for 5 minute events, the maximum time of independency (before a next event hás to be deemed independent) was set at 30 minutes (6 times the event's duration). This means that if a 5 minute event is logged, that event will be the largest 5 minute event in a rolling 30 minute period. The maximum independency times are shown in Table 4.4.2, for the different storm-durations. Note that the maximum independency time was set to 6 hours (in accordance with the Du Plessis study). This means, for example, that if an 18 hour event is logged, the following independent 18 hour event can only commence 6 hours after the end of the first 18 hour event.

Table 4.4.2: Constraints used to select independent storm to be used in analysis. Maximum values shown are in minutes for durations up to 120 minutes, and in hours for durations from 4 hours to 24 hours.

Duration	**Minutes**								**Hours**				
	5	**10**	**15**	**30**	**45**	**60**	**90**	**120**	**4**	**8**	**12**	**18**	**24**
Independency maximum	30	45	60	90	90	120	150	180	6	6	6	6	6

The second step used in this study (from this step onwards, this study's focus differs from that of the Du Plessis study, and the calculation procedure therefore differs as well) was to plot each rainstorm[6], for the different storm durations, recorded at the Molteno station. These graphs were then visually compared. Detailed graphs can be found in Appendix E of this report. Figure 4.4.1, shows the results for the 5 minute duration storms. The figure shows all storms above the pre-defined cut-off minimum (refer Table 4.4.1). It is significant to notice the three extreme events logged in 1996 (32mm in 5 minutes), 2001 (24mm in 5 minutes) and 2002 (22mm in 5 minutes). Prior to these three extreme events, the maximum 5 minute duration rainfall at Molteno was 12mm, measured in 1966. As explained earlier, real-time data was used in the analysis of the information dating from 1956 to 1991, meaning that the peak 5

[6] Only rainstorms deemed independent from the preceding rainstorm were plotted. This means, that the number of events larger than the cut-off cannot be analyzed, as an unknown number of storms have been deleted from the data-set, for not being independent from the preceding event. It must be remembered that the main emphasis of the thesis is the occurrence of peak events (albeit for different storm-durations), and the graphs produced are therefore valid, i.e. the aim is to identify whether an increasing or decreasing trend can be found for the peak event for every storm-duration analyzed.

minute duration rainfall would have been logged. This was however not the case for the data from 1991 to 2003, where 5 minute duration rainfall was analyzed. As explained in the earlier example, the actual peak 5 minutes may not have been recorded, meaning that even more extreme 5 minute rainfall may have occurred in the period after 1991.

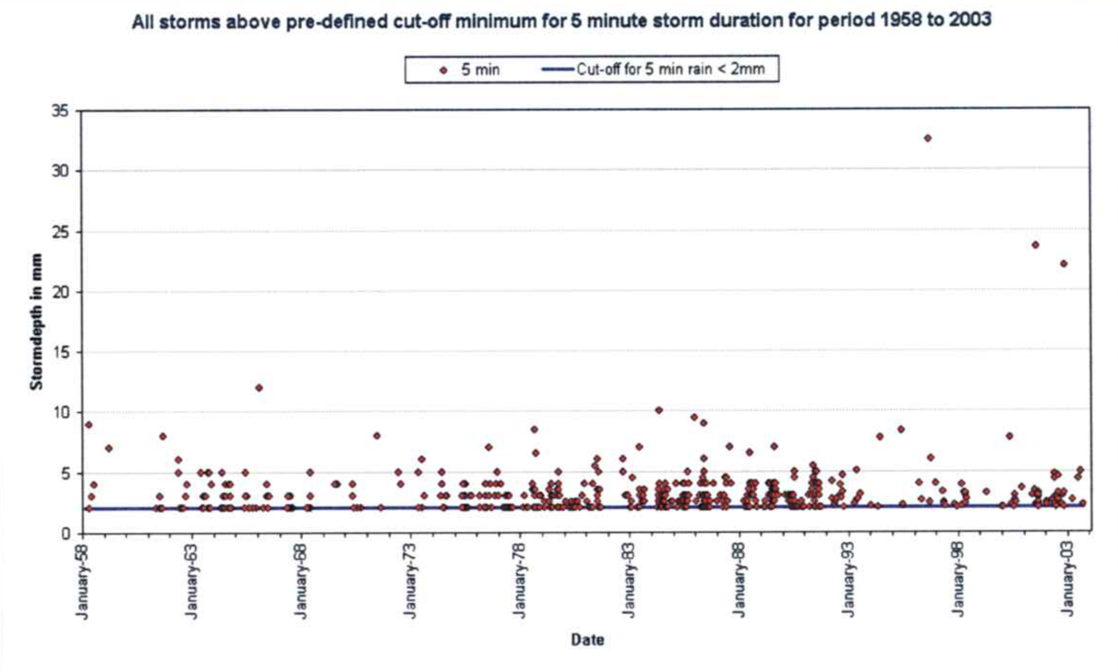


Figure 4.4.1: All storms above pre-determined cut-off for <u>5 minute duration events</u>

Figure 4.4.2 are similar to Figure 4.4.1, Figure 4.4.2 showing all storms above the predetermined cut-off minimum for storm durations of 4 hours.

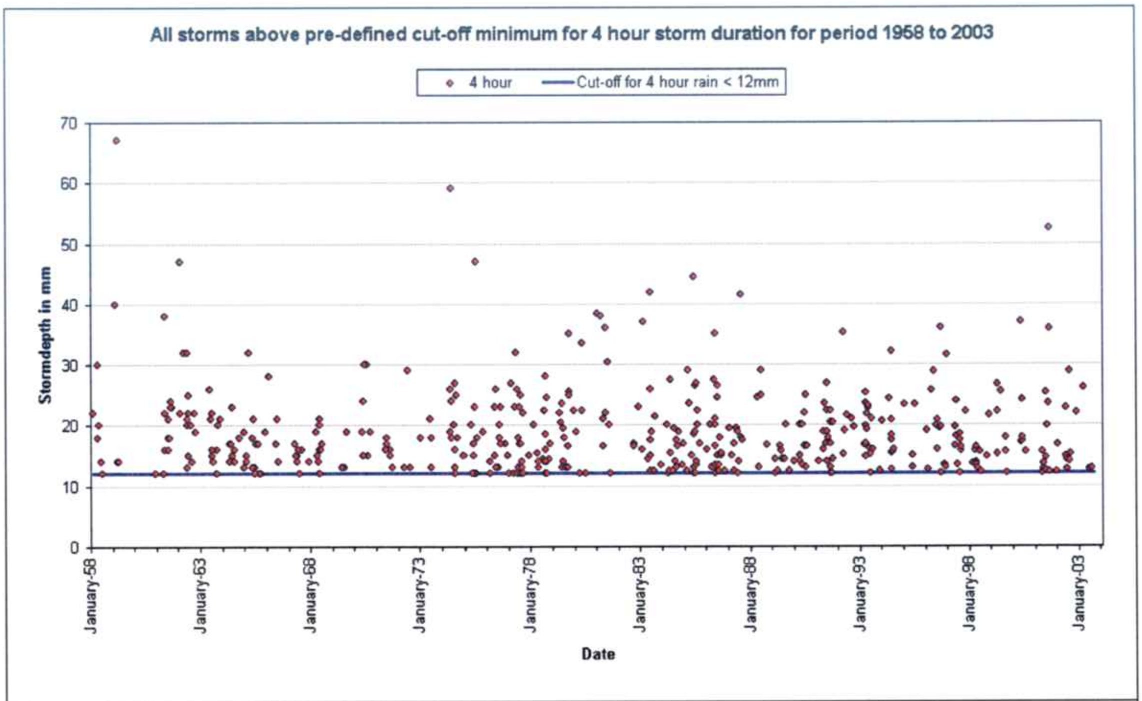


Figure 4.4.2: All storms above pre-determined cut-off for <u>4 hour duration events</u>

It is clear from Figure 4.4.2 that the effect of the extreme 5 minute events measured in the period after 1991 are not significant anymore. In other words, although these events were definitely extreme 5 minute events, a relatively moderate quantity of rainfall were experienced in the preceding period as well as the period following the particular 5 minutes. The same trend could be seen in the graphs for 60 minute duration events, as well as for 24 hour duration events (refer Appendix E for details).

The analysis once again unfortunately did not yield a clear trend towards any discernable change in rainfall patterns, apart from the apparent extreme 5 minute events experienced late in the data set. It was decided to analyze the full data set (1956 to 2003, 5 minute duration rainfall) again. For this analyses no cut-off minimums were applied, implicating that every drop of rainfall recorded at Molteno was included in the analyses. According to the data set, the only rainfall recorded in 1957 and 1960 occurred in November and December of these two years. This is considered to be highly unlikely, and it is considered that a possible anomaly in the measurements and/or recording of the data has occurred. For this reason, the graphs below, as well as the discussion that follows focus on the period 1961 to 2003.

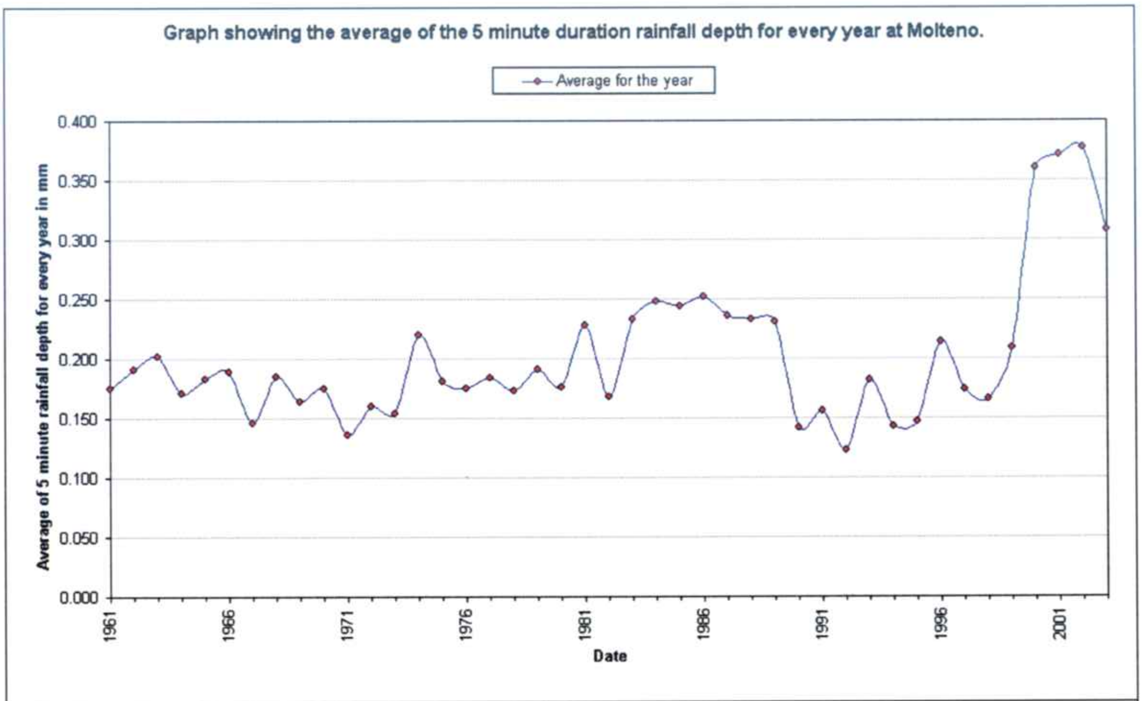


Figure 4.4.3: Graph showing the average 5 minute duration rainfall depth

Figure 4.4.3 shows the average of all 5 minute duration storms for the full data set. It must be noted that zero measurements were not taken into account in the analyses, and that the averages shown are therefore the average of all periods where rainfall was actually recorded. For this reason, not too much significance should be assigned to the actual values on the vertical axes of Figure 4.4.3. The important issue is rather the presence of an increasing or decreasing trend, as explained below.

Despite the occurrence of an extreme 5 minute rainfall event (as highlighted earlier) in 1996, the average 5 minute duration rainfall does not seem un-proportionally high for this year. It can however very clearly be seen that the average 5 minute duration rainfall recorded over the last 4 years are significantly higher than any period before that.

Figure 4.4.4 shows the number of events recorded at Molteno over the analyses period. As no cut-off minimums were applied, this figure shows the actual number of times that (5 minute duration) rainfall was recorded at Molteno.

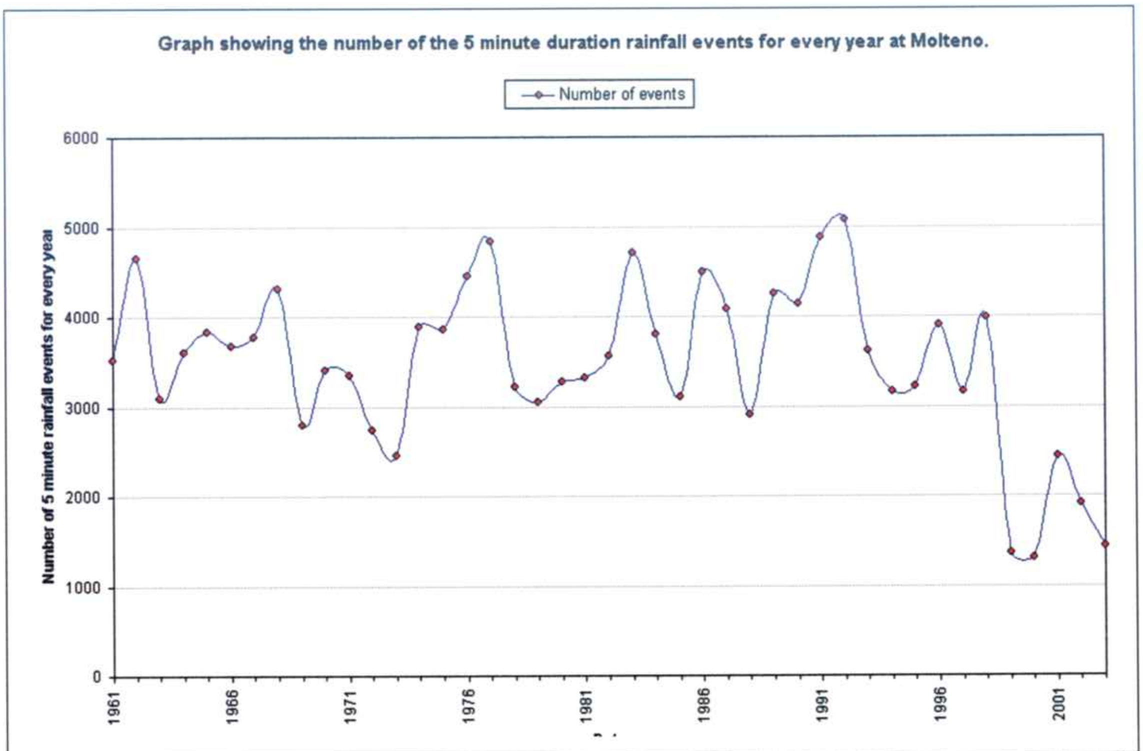


Figure 4.4.4: Graph showing the number of 5 minute duration rainfall events

It is significant to note that the number of events seem to be decreasing, whereas the average rainfall depth could be seen to be increasing, as shown in Figure 4.4.3. This is in accordance with the general expectation that rainfall (intensities) could increase as a result of climate change but the number of rainfall events could decrease.

We must however acknowledge that natural variation in the annual rainfall will occur. In other words, the yearly average will (obviously) not always equal the long-term mean annual precipitation, and dry as well as wet periods could be expected. These periods could last for several years. The question that has to be raised is whether the apparent trend towards increased average rainfall depth (from Figure 4.4.3) and the apparent trend towards decreased number of events (from Figure 4.4.4) could be ascribed to natural annual precipitation variations.

Figure 4.4.5 shows the total yearly precipitation for every year from 1961 to 2003. The green line shows the mean annual precipitation at Molteno as calculated from the data set (1961 to 2003). The value of 677mm is in close correlation to the MAP as obtained from various publications (refer Table 4.3.1) ranging between 610 and 773mm.

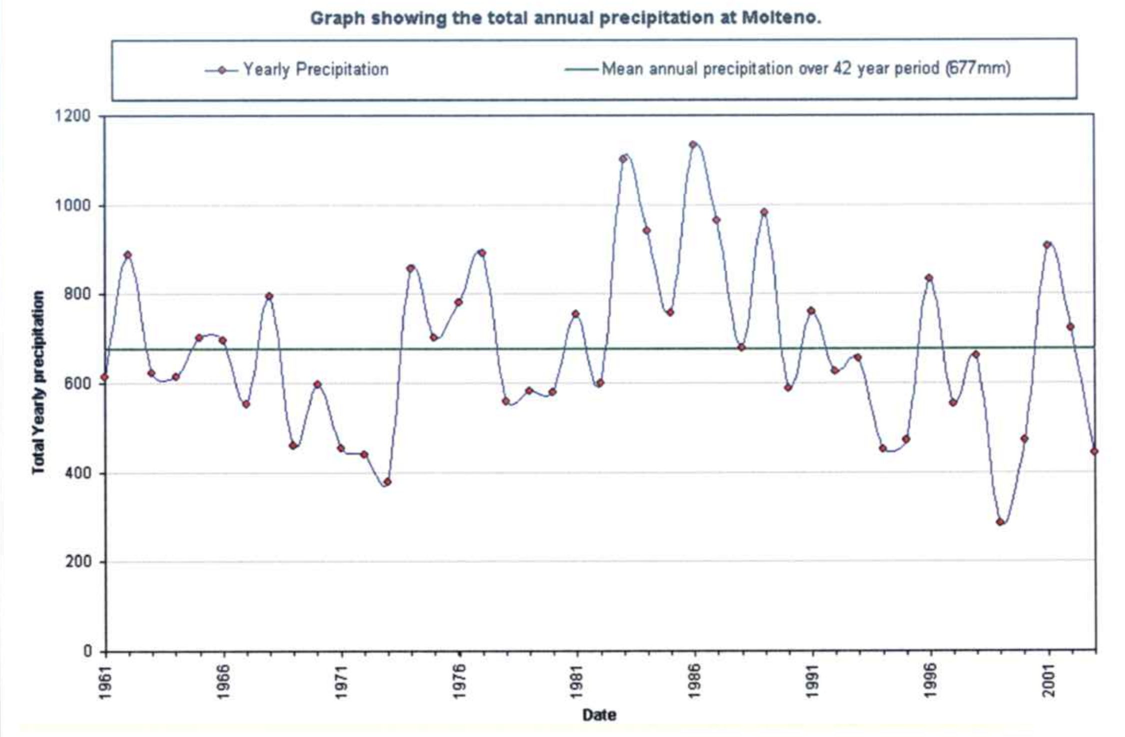


Figure 4.4.5: Graph showing the total annual precipitation at Molteno

It can be seen that the period from ±1983 to ±1991 was clearly a wet period. From ±1969 to ±1974 a dry period was experienced at Molteno. 1991 to 2003 was a relatively dry period, with a couple of wetter years in between. It is however clear from Figure 4.4.4 that fewer rainfall events were recorded in the period from 1999 to 2003. On average, the annual precipitation was not significantly lower in these years. If fewer events were recorded, but the annual rainfall was still more or less the same as in previous years, the obvious conclusion that can be reached is that the intensity of events must have increased. This is in accordance with the findings as detailed in Figure 4.4.3.

The MAP as calculate from the data from 1961 to 2003 is 677mm. The MAP as calculate from the data from 1998 to 2003 is 581mm, representing a theoretical decrease in MAP of 14%. The average yearly number of events when determined for the data set from 1961 to 2003 is 3690. The average yearly number of events when determined for the period from 1998 to 2003 is only 2076, representing a decrease of 44%. It is clear that the number of events is decreasing much more rapidly than the total yearly precipitation which, as explained, will constitute higher intensity rainfall.

Various rolling average trendlines were calculated for the total annual precipitation at Molteno, refer Figure 4.4.6. The purpose of these lines was to investigate the natural periodicity in the precipitation at Molteno, to verify whether the increasing rainfall intensities could simply be ascribed to natural variations. Rolling average lines for periods between five and ten years were determined. These lines indicate the average over the preceding years, i.e. a 5 year rolling average line point shows the average annual precipitation for the preceding 5 years.

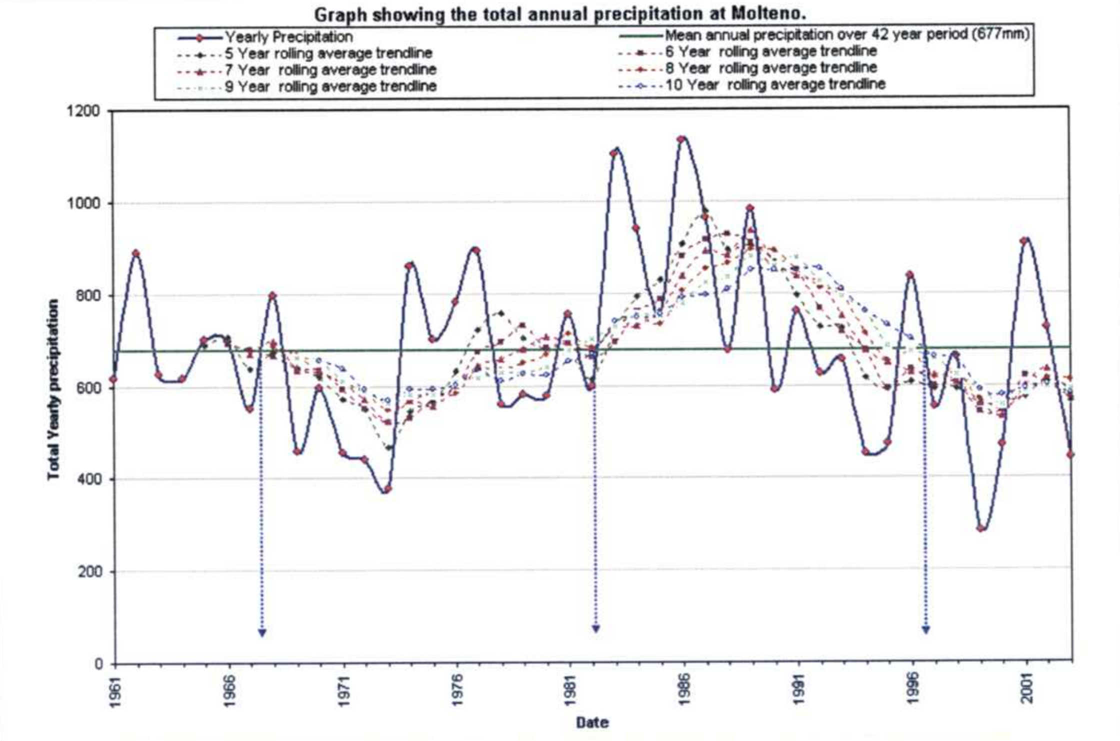


Figure 4.4.6: Graph comparing the total annual precipitation at Molteno with various rolling average lines

It is clear from these lines that irrespective of the rolling period used, the data seems to indicate a dryer period between ±1968 and ±1982 (± 14 years), followed by a wetter period from ±1982 till ±1996 (also ± 14 years long). When we examine the 5-year rolling average line, the above eras shift backwards in time by approximately two to six years.

Irrespective of the line used, the era after 1995 seems to be a dry period, which we can (albeit from a very small sample) expect to last for approximately 14 years. This could partly explain the decrease in the MAP as calculated for the years 1998 to 2003. The very clear increase in the average 5-minute duration event's rainfall depth (Figure 4.4.3) however clearly indicates that despite the fact that the period after 1995 could well be a dry era, 5-minute duration rainfall depths well beyond the average were recorded in the period. This finding indicates that tendencies beyond the variation expected from natural climatic cycles, may have already been recorded, something that could be the result of the enhanced greenhouse effect.

The detailed analysis of the measured data at Molteno, indicated that the rainfall intensities seems to be increasing. Regardless of the lack of a very clear trend (in the initial analysis where the measured data was compared to the predicted data), the apparent increase in the percentage of events of the ± 10mm to ± 40mm range, leads us to conclude that rainfall patterns can be expected to be different in the future, with a trend towards increased medium to large events.

The results of the detailed analyses of 42 years of historical data at Molteno, showed an increase in rainfall intensities over the last four years for 5 minute duration storms, supporting the trend observed when historical data was compared to forecasted data.

The results obtained in this thesis, indicates hydrologists that changing rainfall intensities could be expected in the future for the study area. The next chapter strives to answer the question of how hydrologists should take the possible changes brought about by the enhanced greenhouse effect into consideration.

5. How should hydrologists take the hydrological changes brought about by climate change into consideration?

As mentioned in the introduction, all hydrological predictions are indirectly or directly based on historical data. Empirical formulas and deterministic methods were determined and calibrated from known historical data. Statistical predictions are directly based on actual data. The question that arises is however whether the historical data still provides an accurate basis from which possible future events can be predicted?

It is generally expected that, at the study area, the number of rainfall events could decrease as a result of climate change, but the intensity of the events that do occur, could increase. The main focus of this study is to ascertain whether increased rainfall could be expected for the study area, which would result in increased runoff from sub-catchments. The study area was specifically chosen as an urban area, to eliminate the effect of antecedent moisture conditions, as it can be expected that most sub-catchments in the study area would exhibit nearly 100% hardened surfaces, with very little infiltration occurring. The result is that an increase in rainfall should manifest in a similar increase in runoff. As most of the stormwater systems in the study area have been developed, and sized from historical rainfall intensities, an increase in rainfall intensities could result in the functional failure of certain stormwater systems.

It is also important to note that hydrologists are understandably keen to utilize rainfall records that are as long as possible. This should generally ensure that any short-term climate or measuring "irregularities or abnormalities" will be either, identified and removed from the record (as could be the case with outliers in a data record), or will be "diffused" by the long record.

If we find that a certain area's climate are changing as a result of external forces – as is the case with climate change – the question arises whether the changing patterns can be grouped together with the unchanged patters. In other words, if climate change has an effect on rainfall patterns (be it an increase or a decrease), is it sensible to group rainfall data from the greenhouse era together with data from the enhanced greenhouse era and to establish long-term trends from the combined data set?

This might mean that hydrologists in the future could find themselves in a position where they have 100 - 150 years of data of which 50 years are from the period which is generally accepted to be a pre-climate change era. The historical 1:10 year recurrence interval rainfall intensity (for a given storm duration) could, for arguments sake, be 30mm per hour at a certain position. If, for instance, rainfall intensities have increased at that particular site as a result of the enhanced greenhouse effect, the post-climate change 1:10 year recurrence interval rainfall intensity for the same storm duration could perhaps have increased to 40mm per hour. This is obviously the rainfall intensity that the hydrologist should design for, as it is the expected intensity at that time in the future (enhanced greenhouse effect era). If the two data sets (historical and enhanced greenhouse effect era) were combined, the 1:10 year rainfall intensity may be calculated as 35mm per hour, which would imply that the hydrologist is underestimating the intensity, and if antecedent moisture conditions can be excluded from the calculations (as explained earlier), the designer will under-design the stormwater system.

It was anticipated that clearer trends towards an increased percentage of larger rainfall events would be found, for the future data at the rainfall stations investigated. The increase of around 6-11% for percentage of occurrence of the 20-40mm range of 24-hour rainfall, is however alarming. This shows that, for the study area, rainfall intensities cán be expected to increase, and therefore hydrologists should take due diligence in analyzing any data set in the future, as it may include data from both pre- as well as post-climate change eras, and combining these may underestimate rainfall intensities, as explained earlier.

It is acknowledged that the trend towards increased intensities was not very clear, and that if rainfall intensities should in fact decrease, combining the pre- and post-climate change data could over-estimate intensities. This could however lead to un-economical designs. It is therefore apparent that any change in rainfall patters, if not properly addressed in the analysis of the hydrologist, could either lead to unsafe- or uneconomical designs. Hydrologists should therefore attempt to identify any shorter-term trends within their data set, and apply their minds as to the possible consequences of combining the whole data set, and statistically analyzing the full data set. It is important to note that the use of short duration rainfall records are not advocated, rather that hydrologists should be cautious when analyzing long data sets.

The detailed analysis of all the rainfall events at Molteno reservoir did however yield very clear trends. It was clearly shown that despite the fairly constant total yearly precipitation, the number of rainfall events seems to be decreasing much more significantly, with a very apparent decrease in the number of events after 1998. The logical deduction is that rainfall intensities must have increased in this period, to sustain the total yearly precipitation. This trend towards increased intensities was underlined when the average 5 minute duration rainfall depth was plotted (refer Figure 4.4.3). Based on 5 minute duration rainfall, the conclusion can be drawn that the number of 5 minute rainfall events decreased significantly (Figure 4.4.4) and the total yearly precipitation decrease much less (Figure 4.4.5). This clearly indicates that the intensity of the 5 minute rainfall events must have increased, to sustain the total yearly precipitation.

6. Conclusions and recommendations

The historical 24-hour rainfall was analyzed in two different ways, for 5 different stations near the study area. Historical, control and forecasted data was initially transformed to sub 24-hour intensities by using known relationships derived from historical figures. The control and forecasted data were then plotted and compared to IDF curves as calculated by City of Cape Town, as well as IDF curves as determined from the well known Stephenson and Op ten Noort equation. It was acknowledged that the forecasted data should not be transformed to sub 24-hour intensities by means of the Adamson ratios, because these ratios will probably not be applicable to the forecasted data. It was then decided to compare the historical and forecasted data in a different way. The methodology followed in this part of the study, was to determine the percentage of occurrence of 24-hour rainfall, of pre-defined ranges of magnitude, for the historical as well as the forecasted data. The percentage of occurrence of the various ranges of 24-hour rainfall, were then compared, and possible trends were investigated.

It was found that an apparent trend towards increased percentage of events for the ± 10 mm to ± 40 mm 24-hour rainfall events could be expected. As mentioned in chapter 4, this trend was however not significant. It was also shown that from the detailed analyses of the actual rainfall at Molteno, an increase in intensity of rainfall has occurred for the period from 1999 to 2003. In Chapter 5 it was argued that, in line with general scientific expectations with respect to climate change and its influence on rainfall, rainfall intensities could well be expected to change in future. Two possible scenarios were described in Chapter 5, the first being a scenario where rainfall intensities might increase as a result of climate change, and the second where rainfall intensities would in fact decrease as a result of climate change. It was reasoned that the first scenario could lead to under estimating of rainfall intensities if very long rainfall records are analyzed (records containing both "changed- and unchanged" rainfall data). The second scenario could lead to uneconomical designs, if rainfall intensities are over-estimated.

Climate change is unfortunately a very uncertain science. We are dealing with a highly complex climate system, with interaction from atmospheric gases, the effect of varying solar radiation as a result of the earth's seasonal orientation with regards to the sun, the earth's topography which might influence the formation of clouds and cloud cover subsequently influencing photosynthesis to name but a few. To add to this highly complex system, the effect of changing concentrations of greenhouse gases has to be taken into account. To even further enhance the uncertainties, we are trying to extrapolate the effect that enhanced greenhouse gases might have on this intricately balanced system, up to 100 years into the future!

It is clear that we are dealing with a topic which commands our respect, and one for which we could only claim to be marginally capable of extrapolating future trends. The many uncertainties do not however mean that scientist should dissociate themselves from research in this field. The importance as well as possible severe consequences of climate change should encourage role-players to support those scientists bold enough to do research in this field, and as a result of the possible severe consequence that climate change could have for life on earth, any possible trends that are identified should be investigated further.

Studies similar to this one should be repeated at regular intervals in the future, to verify if the expected trends are in fact occurring. We must however once again emphasize that natural climatic cycles do occur. We should endeavor to adapt to these natural cycles. This study focused on the possible consequence of the enhanced greenhouse effect on rainfall intensities, in other words, the influence of humans' industrial actions on the climate systems. These influences should be identified, and we should attempt to slow-down or reverse the negative consequences of the enhanced greenhouse effect. In other words, the important issue is to try and recognize the **super-imposed effect of mans' actions**, and to try and either reverse or slow down that effect, or to be aware of the result of our actions. When more measured rainfall data becomes available emanating from the so-called "climate changed era[7]", this data should be compared to data from the "pre-climate change era." This could lead to enhanced understanding of the effect that climate change has

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[7] Identified in this study as the era after humans' influence may have had an effect on the natural climate cycles

on rainfall intensities, and possible trends could become more evident. As this study focused on a very small urban catchment only, it is recommended that the study be expanded to include a wider spatial distribution of rainfall stations, possibly including rural catchment areas as well. By including more rainfall stations in the study and expanding the spatial distribution of the study area, the credibility of the study could be hugely enhanced, and clearer trends could become apparent.

In conclusion it can be mentioned that although overwhelmingly clear trends were not initially identified in this study, possible trends towards increased percentage of occurrence of higher 24-hour rainfall events were identified, and the result of such changes were discussed. In addition to the comparison of forecasted to measured data a detailed analyses of the actual measurements for a 42 year period (1961 to 2003) at Molteno reservoir showed a very clear trend towards increased intensities for the period 1999 to 2003. Although the detailed study was only performed at one rainfall station, the trend of increased intensities already experienced at that station is very alarming. It seems as if changes to the rainfall patterns could be occurring, possibly as a result of climate change.

Hydrologists should consider these possible changes in analyzing rainfall data in the future, and should guard against the use of rainfall data or intensity- formula or relationships which had been derived from historical data, as these may not display the same characteristics as the climate at that time.

The main research questions identified in the methodology were as follows:

- Does climate change models predict an increase in storms at Molteno station (located in the study area), based on 24-hour rainfall events?
- If the above can be found to be true, does it also apply to the general region?
- Can these findings be confirmed through the analysis of short duration rainfall events (historical data)?

The conclusions reached in this study addressing the above questions, can be summarized as follows:

- The IDF-curve investigation did not yield sensible results, probably as a result of the use of Adamson ratio's on forecasted rainfall data;

- The percentage of occurrence of 24-hour rainfall of larger magnitudes seemed to increase for the Molteno rainfall station, when the historical data are compared to forecasted data (Research question one);
- The trend of increase of percentage of occurrence of larger 24-hour events, were not as apparent when 5 stations near the study area's results were combined, or for the individual results at the four additional stations (Research question two);
- The 5 minute intensity of rainfall at Molteno station for the period 1998 to 2003 is clearly higher than for any period before then, refer Figure 4.4.3 (Research question three);
- It is generally expected that changes in rainfall patterns could occur as a result of climate change (or rather the human influence on the natural climate cycles), and therefore the combination of rainfall data from the "greenhouse era" with rainfall data from the enhanced greenhouse era could under- or overestimate expected rainfall in the future;
- Hydrologists should be cautious of analyzing long historical data sets in future, as these could include both pre- as well as post-climate change data.

The recommendation made in this report can be summarized as follows:

- Studies similar to this one should be repeated in the future, to monitor possible changes;
- The study could be expanded to include a wider spatial distribution, possibly including rural catchment areas.

7. References

1. Centre for Ecology and Hydrology, Natural Environment. www.ceh-nerc.ac.uk/science-topics/science-projects/climate.htm
2. Climate change education. www.climatechangeeducation.org
3. Climate Change Information Kit, published by the United Nations Environment Programme (UNEP) and the United Nations Framework Convention on Climate change (UNFCCC).
4. Columbia University, New York. www.earthscape.org/t1/unep01/unep10.html
5. Climate Systems Analysis Group (CSAG) at the University of Cape Town. www.csag.uct.ac.za – Professor Bruce Hewitson and Ruwani Walawege
6. Department of Water Affairs and Forestry (DWAF). www.dwaf.gov.za/sd/presentations/wwf-files/frame.htm
7. Hydrology 414 Class notes, Professor A. Görgens, Stellenbosch University.
8. National Academics, Science Museum. www.koshlandscience.org/exhibitgcc/index.jsp
9. National Biodiversity Institute. www.nbi.ac.za/climrep.index.html
10. News24 – Various articles on www.news24.com
11. Personal communication – J.A. du Plessis
12. Rainfall – Intensity-duration-frequency curves for the City of Cape Town, J.A. du Plessis et al
13. The Regional impacts of Climate change, Intergovernmental Panel on Climate change, http://www.grida.no/climate/ipcc/regional/index.htm
14. United Nations Environment programme. www.grida.no/climate/vital/index.htm
15. United Nations Framework convention on climate change, http://unfccc.int/essential_background/kyoto_protocol/items/2830.php
16. Water Research Commission publications. www.wrc.org.za/publications_waterwheel.htm
17. South African Weather bureau. www.weathersa.co.za/references/climchange.jsp
18. Wageningen University and research centre, http://www.wageningen-ur.nl/

Appendix A:

Status of ratification of Kyoto protocol as on 29 April 2005

Last modified on: 29 April 2005

KYOTO PROTOCOL

STATUS OF RATIFICATION

Notes:

R = Ratification
At = Acceptance
Ap = Approval
Ac = Accession

COUNTRY	SIGNATURE	RATIFICATION, ACCEPTANCE, ACCESSION, APPROVAL	REMARKS	% of emissions
1. ALBANIA		01/04/05 (Ac)		
2. ANTIGUA AND BARBUDA	16/03/98	03/11/98 (R)		
3. ARGENTINA	16/03/98	28/09/01 (R)		
4. ARMENIA	----	25/04/03 (Ac)		
5. AUSTRALIA*	29/04/98			
6. AUSTRIA*	29/04/98	31/05/02 (R)		0.4%
7. AZERBAIJAN	-----	28/09/00 (Ac)		
8. BAHAMAS	-----	09/04/99 (Ac)		
9. BANGLADESH	-----	22/10/01 (Ac)		
10. BARBADOS	-----	07/08/00 (Ac)		
11. BELGIUM*	29/04/98	31/05/02 (R)		0.8%
12. BELIZE	-----	26/09/03 (Ac)		
13. BENIN	-----	25/02/02 (Ac)		
14. BHUTAN	-----	26/08/02 (Ac)		
15. BOLIVIA	09/07/98	30/11/99 (R)		
16. BOTSWANA	-----	08/08/03 (Ac)		
17. BRAZIL	29/04/98	23/08/02 (R)		
18. BULGARIA*	18/09/98	15/08/02 (R)		0.6%
19. BURKINA FASO		31/03/05 (Ac)		
20. BURUNDI	-----	18/10/01 (Ac)		
21. CAMBODIA	-----	22/08/02 (Ac)		
22. CAMEROON	-----	28/08/02 (Ac)		
23. CANADA*	29/04/98	17/12/02 (R)		3.3%

* indicates an Annex I Party to the United Nations Framework Convention on Climate Change.

Last modified on: 29 April 2005

COUNTRY	SIGNATURE	RATIFICATION, ACCEPTANCE, ACCESSION, APPROVAL	REMARKS	% of emissions
24. CHILE	17/06/98	26/08/02 (R)		
25. CHINA	29/05/98	30/08/02 (Ap)	(10)	
26. COLOMBIA	-----	30/11/01 (Ac)		
27. COOK ISLANDS	16/09/98	27/08/01 (R)	(4)	
28. COSTA RICA	27/04/98	09/08/02 (R)		
29. CROATIA*	11/03/99			
30. CUBA	15/03/99	30/04/02 (R)		
31. CYPRUS	-----	16/07/99 (Ac)		
32. CZECH REPUBLIC*	23/11/98	15/11/01 (Ap)		1.2%
33. DEMOCRATIC REPUBLIC OF CONGO		23/03/05 (Ac)		
34. DEMOCRATIC PEOPLE'S REPUBLIC OF KOREA	-----	27/04/05 (Ac)		
35. DENMARK*	29/04/98	31/05/02 (R)[1]		0.4%
36. DJIBOUTI	-----	12/03/02 (Ac)		
37. DOMINICA	-----	25/01/05 (Ac)		
38. DOMINICAN REPUBLIC	-----	12/02/02 (Ac)		
39. ECUADOR	15/01/99	13/01/00 (R)		
40. EGYPT	15/03/99	12/01/05 (R)		
41. EL SALVADOR	08/06/98	30/11/98 (R)		
42. EQUATORIAL GUINEA	-----	16/08/00 (Ac)		
43. ESTONIA*	03/12/98	14/10/02 (R)		0.3%
44. ETHIOPIA	-----	14/04/05 (Ac)		
45. EUROPEAN COMMUNITY*	29/04/98	31/05/02 (Ap)	(1) (8)	
46. FIJI	17/09/98	17/09/98 (R)		
47. FINLAND*	29/04/98	31/05/02 (R)		0.4%
48. FRANCE*	29/04/98	31/05/02 (Ap)	(2) (9)	2.7%
49. GAMBIA	-----	01/06/01 (Ac)		
50. GEORGIA	-----	16/06/99 (Ac)		
51. GERMANY*	29/04/98	31/05/02 (R)		7.4%

[1] With a territorial exclusion to the Faroe Islands.

* indicates an Annex I Party to the United Nations Framework Convention on Climate Change.

Last modified on: 29 April 2005

COUNTRY	SIGNATURE	RATIFICATION, ACCEPTANCE, ACCESSION, APPROVAL	REMARKS	% of emissions
52. GHANA	-----	30/05/03 (Ac)		
53. GREECE*	29/04/98	31/05/02 (R)		0.6%
54. GRENADA	-----	06/08/02 (Ac)		
55. GUATEMALA	10/07/98	05/10/99 (R)		
56. GUINEA	-----	07/09/00 (Ac)		
57. GUYANA	-----	05/08/03 (Ac)		
58. HONDURAS	25/02/99	19/07/00 (R)		
59. HUNGARY*	-----	21/08/02 (Ac)		0.5%
60. ICELAND*	-----	23/05/02 (Ac)		0.0%
61. INDIA	-----	26/08/02 (Ac)		
62. INDONESIA	13/07/98	03/12/04(R)		
63. IRELAND*	29/04/98	31/05/02 (R)	(3)	0.2%
64. ISRAEL	16/12/98	15/03/04 (R)		
65. ITALY*	29/04/98	31/05/02 (R)		3.1%
66. JAMAICA	-----	28/06/99 (Ac)		
67. JAPAN*	28/04/98	04/06/02 (At)		8.5%
68. JORDAN	-----	17/01/03 (Ac)		
69. KAZAKHSTAN	12/03/99			
70. KENYA		25/02/05 (Ac)		
71. KIRIBATI	-----	07/09/00 (Ac)	(6)	
72. KUWAIT	-----	11/03/05 (Ac)		
73. KYRGYZSTAN	-----	13/05/03 (Ac)		
74. LAO DEMOCRATIC PEOPLE'S REPUBLIC	-----	06/02/03 (Ac)		
75. LATVIA*	14/12/98	05/07/02 (R)		0.2%
76. LESOTHO	-----	06/09/00 (Ac)		
77. LIBERIA	-----	05/11/02 (Ac)		
78. LIECHTENSTEIN*	29/06/98	03/12/04 (R)		
79. LITHUANIA*	21/09/98	03/01/03 (R)		
80. LUXEMBOURG*	29/04/98	31/05/02 (R)		0.1%

* indicates an Annex I Party to the United Nations Framework Convention on Climate Change.

Last modified on: 29 April 2005

COUNTRY	SIGNATURE	RATIFICATION, ACCEPTANCE, ACCESSION, APPROVAL	REMARKS	% of emissions
81. MADAGASCAR	-----	24/09/03 (Ac)		
82. MALAWI	-----	26/10/01 (Ac)		
83. MALAYSIA	12/03/99	04/09/02 (R)		
84. MALDIVES	16/03/98	30/12/98 (R)		
85. MALI	27/01/99	28/03/02 (R)		
86. MALTA	17/04/98	11/11/01 (R)		
87. MARSHALL ISLANDS	17/03/98	11/08/03 (R)		
88. MAURITIUS	-----	09/05/01 (Ac)		
89. MEXICO	09/06/98	07/09/00 (R)		
90. MICRONESIA (FEDERATED STATES OF)	17/03/98	21/06/99 (R)		
91. MONACO*	29/04/98			
92. MONGOLIA	-----	15/12/99 (Ac)		
93. MOROCCO	-----	25/01/02 (Ac)		
94. MOZAMBIQUE	-----	18/01/05 (Ac)		
95. MYANMAR	-----	13/08/03 (Ac)		
96. NAMIBIA	-----	04 /09/03 (Ac)		
97. NAURU	-----	16/08/01 (R)	(7)	
98. NETHERLANDS*	29/04/98	31/05/02 (At)[2]		1.2%
99. NEW ZEALAND*	22/05/98	19/12/02 (R)[3]	(11)	0.2%
100. NICARAGUA	07/07/98	18/11/99 (R)		
101. NIGER	23/10/98	30/09/04 (R)		
102. NIGERIA	-----	10/12/04 (Ac)		
103. NIUE	08/12/98	06/05/99 (R)	(5)	
104. NORWAY*	29/04/98	30/05/02 (R)		0.3%
105. OMAN	-----	19/01/05 (Ac)		
106. PAKISTAN	-----	11/01/05 (Ac)		
107. PALAU	-----	10/12/99 (Ac)		

2 For the Kingdom in Europe.
3 with a territorial exclusion to Tokelau.

* indicates an Annex I Party to the United Nations Framework Convention on Climate Change.

Last modified on: 29 April 2005

COUNTRY	SIGNATURE	RATIFICATION, ACCEPTANCE, ACCESSION, APPROVAL	REMARKS	% of emissions
108. PANAMA	08/06/98	05/03/99 (R)		
109. PAPUA NEW GUINEA	02/03/99	28/03/02 (R)		
110. PARAGUAY	25/08/98	27/8/99 (R)		
111. PERU	13/11/98	12/09/02 (R)		
112. PHILIPPINES	15/04/98	20/11/03 (R)		
113. POLAND*	15/07/98	13/12/02 (R)		3,0%
114. PORTUGAL*	29/04/98	31/05/02 (Ap)		0.3%
115. QATAR	-----	11/01/05 (Ac)		
116. REPUBLIC OF KOREA	25/09/98	08/11/02 (R)		
117. REPUBLIC OF MOLDOVA	-----	22/04/03 (Ac)		
118. ROMANIA*	05/01/99	19/03/01 (R)		1.2%
119. RUSSIAN FEDERATION*	11/03/99	18/11/04 (R)		17.4%
120. RWANDA	-----	22/07/04 (Ac)		
121. SAINT LUCIA	16/03/98	20/08/03 (R)		
122. SAINT VINCENT AND THE GRENADINES	19/03/98	31/12/04 (R)		
123. SAMOA	16/03/98	27/11/00 (R)		
124. SAUDI ARABIA	-----	31/01/05 (Ac)		
125. SENEGAL	-----	20/07/01 (Ac)		
126. SEYCHELLES	20/03/98	22/07/02 (R)		
127. SLOVAKIA*	26/02/99	31/05/02 (R)		0.4%
128. SLOVENIA*	21/10/98	02/08/02 (R)		
129. SOLOMON ISLANDS	29/09/98	13/03/03 (R)		
130. SOUTH AFRICA	-----	31/07/02 (Ac)		
131. SPAIN*	29/04/98	31/05/02 (R)		1.9%
132. SRI LANKA	-----	03/09/02 (Ac)		
133. SUDAN	-----	02/11/04 (Ac)		
134. SWEDEN*	29/04/98	31/05/02 (R)		0.4%
135. SWITZERLAND*	16/03/98	09/07/03 (R)		0.3%%
136. THAILAND	02/02/99	28/08/02 (R)		

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COUNTRY	SIGNATURE	RATIFICATION, ACCEPTANCE, ACCESSION, APPROVAL	REMARKS	% of emissions
137. THE FORMER YUGOSLAV REPUBLIC OF MACEDONIA	-----	18/11/04 (Ac)		
138. TOGO	-----	02/07/04 (Ac)		
139. TRINIDAD AND TOBAGO	07/01/99	28/01/99 (R)		
140. TUNISIA	-----	22/01/03 (Ac)		
141. TURKMENISTAN	28/09/98	11/01/99 (R)		
142. TUVALU	16/11/98	16/11/98 (R)		
143. UGANDA	-----	25/03/02 (Ac)		
144. UKRAINE*	15/03/99	12/04/04 (R)		
145. UNITED ARAB EMIRATES	-----	26/01/05 (Ac)		
146. UNITED KINGDOM OF GREAT BRITAIN AND NORTHERN IRELAND*	29/04/98	31/05/02 (R)		4.3%
147. UNITED REPUBLIC OF TANZANIA	-----	26/08/02 (Ac)		
148. UNITED STATES OF AMERICA*	12/11/98			
149. URUGUAY	29/07/98	05/02/01 (R)		
150. UZBEKISTAN	20/11/98	12/10/99 (R)		
151. VANUATU	-----	17/07/01 (Ac)		
152. VENEZUELA		18/02/05 (Ac)		
153. VIET NAM	03/12/98	25/09/02 (R)		
154. YEMEN	-----	15/09/04 (Ac)		
155. ZAMBIA	05/08/98			
TOTAL	84	150	-----	61.6%

* indicates an Annex I Party to the United Nations Framework Convention on Climate Change.

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DECLARATIONS

(1) European Community:

"The European Community and its Member States will fulfil their respective commitments under article 3, paragraph 1, of the Protocol jointly in accordance with the provisions of article 4."

(2) France:

"The French Republic reserves the right, in ratifying the Kyoto Protocol to the United Nations Framework Convention on Climate Change, to exclude its Overseas Territories from the scope of the Protocol."

(3) Ireland:

"The European Community and the Member States, including Ireland, will fulfil their respective commitments under article 3, paragraph 1, of the Protocol in accordance with the provisions of article 4."

(4) Cook Islands:

"The Government of the Cook Islands declares its understanding that signature and subsequent ratification of the Kyoto Protocol shall in no way constitute a renunciation of any rights under international law concerning State responsibility for the adverse effects of the climate change and that no provision in the Protocol can be interpreted as derogating from principles of general international law.

In this regard, the Government of the Cook Islands further declares that, in light of the best available scientific information and assessment on climate change and its impacts, it considers the emissions reduction obligation in article 3 of the Kyoto Protocol to be inadequate to prevent dangerous anthropogenic interference with the climate system."

(5) Niue:

"The Government of Niue declares its understanding that ratification of the Kyoto Protocol shall in no way constitute a renunciation of any rights under international law concerning state responsibility for the adverse effects of climate change and that no provisions in the Protocol can be interpreted as derogating from the principles of general international law.

In this regard, the Government of Niue further declares that, in light of the best available scientific information and assessment of climate change and impacts, it considers the emissions reduction obligations in Article 3 of the Kyoto Protocol to be inadequate to prevent dangerous anthropogenic interference with the climate system."

(6) Kiribati:

"The Government of the Republic of Kiribati declares its understanding that accession to the Kyoto Protocol shall in no way constitute a renunciation of any rights under international law concerning State responsibility for the adverse effects of the climate change and that no provision in the Protocol can be interpreted as derogating from principles of general international law."

(7) Nauru

"... The Government of the Republic of Nauru declares its understanding that the ratification of the Kyoto Protocol shall in no way constitute a renunciation of any rights under international law concerning State responsibility for the adverse effects of climate change; ...
... The Government of the Republic of Nauru further declares that, in the light of the best available scientific information and assessment of climate change and impacts, it considers the emissions of reduction obligations in Article 3 of the Kyoto Protocol to be inadequate to prevent the dangerous anthropogenic interference with the climate system;
... [The Government of the Republic of Nauru declares] that no provisions in the Protocol can be interpreted as derogating from the principles of general international law[.]

(8) European Community:

"The European Community declares that, in accordance with the Treaty establishing the European Community, and in particular article 175 (1) thereof, it is competent to enter into international agreements, and to implement the obligations resulting therefrom, which contribute to the pursuit of the following objectives:

- preserving, protecting and improving the quality of the environment;
- protecting human health;
- prudent and rational utilisation of natural resources;
- promoting measures at international level to deal with regional or world wide environmental problems.

The European Community declares that its quantified emission reduction commitment under the Protocol will be fulfilled through action by the Community and its Member States within the respective competence of each and that it has already adopted legal instruments, binding on its Member States, covering matters governed by the Protocol.

The European Community will on a regular basis provide information on relevant Community legal instruments within the framework of the supplementary information incorporated in its national communication submitted under article 12 of the Convention for the purpose of demonstrating compliance with its commitments under the Protocol in accordance with article 7 (2) thereof and the guidelines thereunder."

(9) France:

"The ratification by the French Republic of the Kyoto Protocol to the United Nations Framework Convention on Climate Change of 11 December 1997 should be interpreted in the context of the commitment assumed under article 4 of the Protocol by the European Community, from which it is indissociable. The ratification does not, therefore, apply to the Territories of the French Republic to which the Treaty establishing the European Community is not applicable.

Nonetheless, in accordance with article 4, paragraph 6, of the Protocol, the French Republic shall, in the event of failure to achieve the total combined level of emission reductions, remain individually responsible for its own level of emissions."

(10) China:

In a communication received on 30 August 2002, the Government of the People's Republic of China informed the Secretary-General of the following:

"In accordance with article 153 of the Basic Law of the Hong Kong Special Administrative Region of the People's Republic of China of 1990 and article 138 of the Basic Law of the Macao Special

Administrative Region of the People's Republic of China of 1993, the Government of the People's Republic of China decides that the Kyoto Protocol to the United Nations Framework Convention on Climate Change shall provisionally not apply to the Hong Kong Special Administrative Region and the Macao Special Administrative Region of the People's Republic of China."

(11) New Zealand:

".....consistent with the constitutional status of Tokelau and taking into account the commitment of the Government of New Zealand to the development of self-government for Tokelau through an act of self-determination under the Charter of the United Nations, this ratification shall not extend to Tokelau unless and until a Declaration to this effect is lodged by the Government of New Zealand with the Depositary on the basis of appropriate consultation with that territory."

Appendix B:

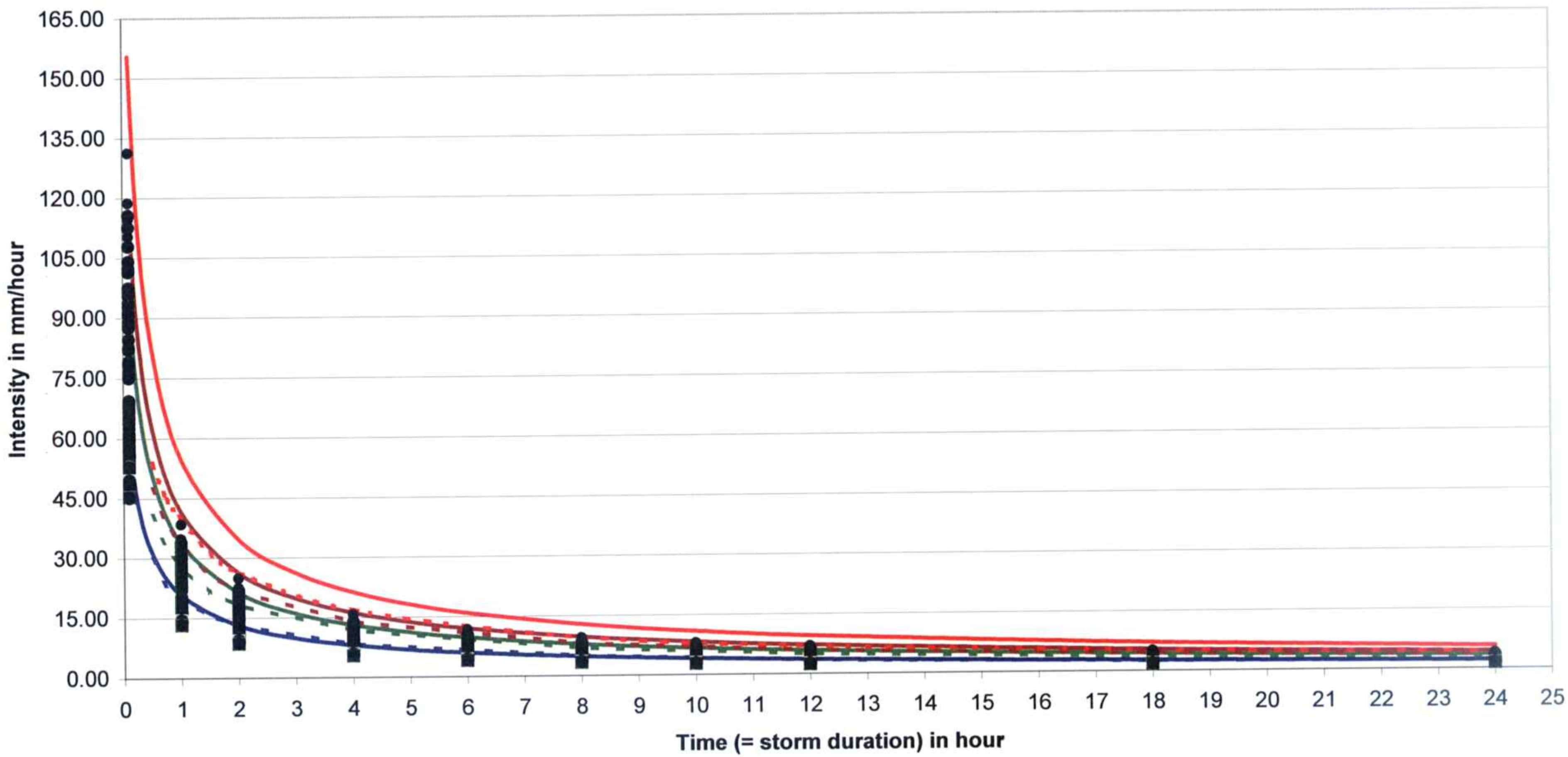
Analysis of historical, control and forecated rainfall data on the basis of IDF curves, for City of Cape Town – City Bowl

Appendix B1:

IDF curves for long historical data set at Molteno-reservoir

Points derived from Historical data (showing the 150 largest events in 46 year period) using Adamson coastal region ratios for sub-24-hour durations

IDF curves shown are from *Stephenson and Op ten Noort* (solid lines) for MAP = 700mm and a coastal zone, as well as JA du Plessis (dashed lines) for City of Cape Town
Curves shown are for recurrence intervals 2 (blue), 10 (green), 20 (brown) and 50 (red) years

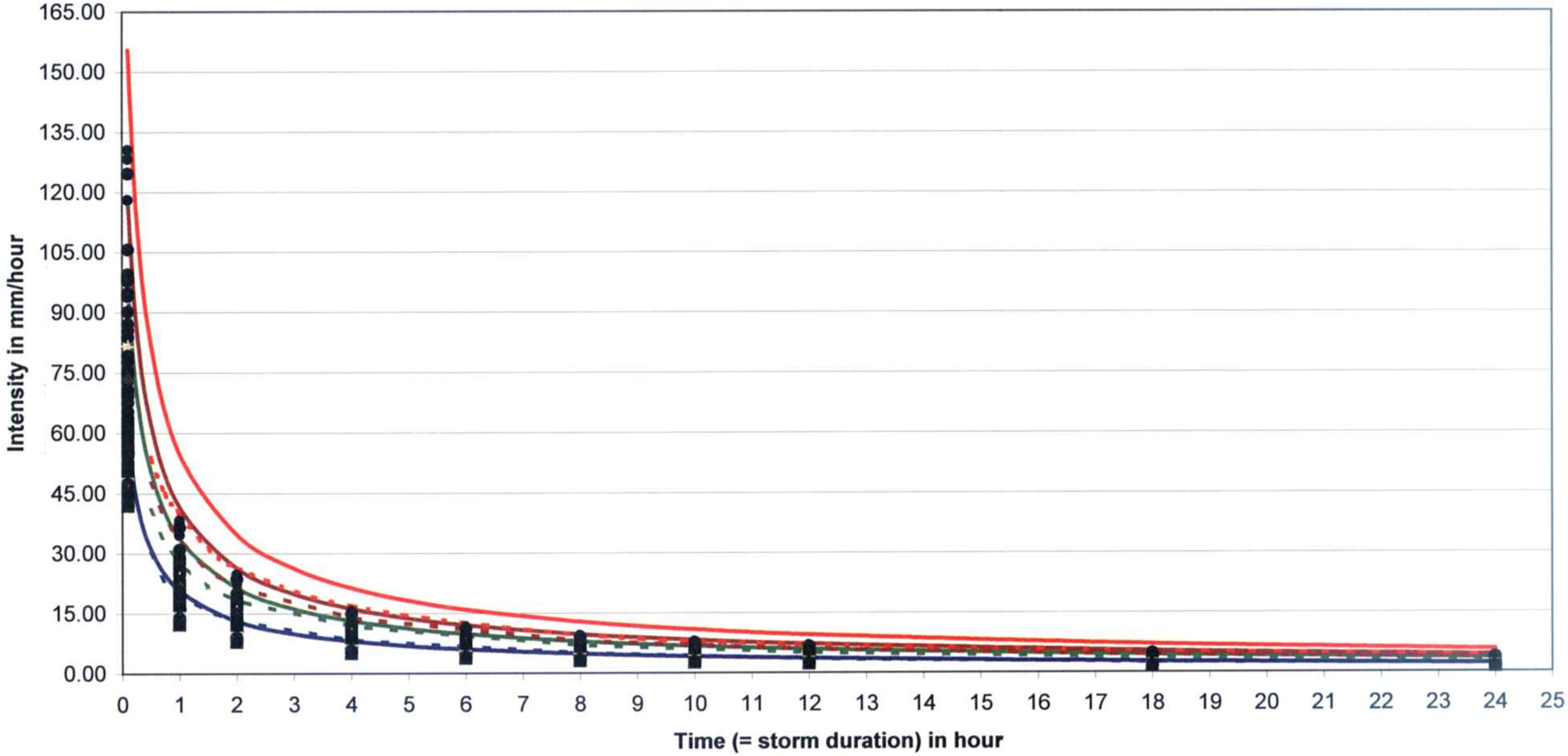


Appendix B2:

IDF curves for short historical data set at Molteno-reservoir

Points derived from short Historical data (showing the 150 largest events in 21 year period) using Adamson coastal region ratios for sub-24-hour durations

IDF curves shown are from *Stephenson and Op ten Noort* (solid lines) for MAP = 700mm and a coastal zone, as well as JA du Plessis (dashed lines) for City of Cape Town
Curves shown are for recurrence intervals 2 (blue), 10 (green), 20 (brown) and 50 (red) years

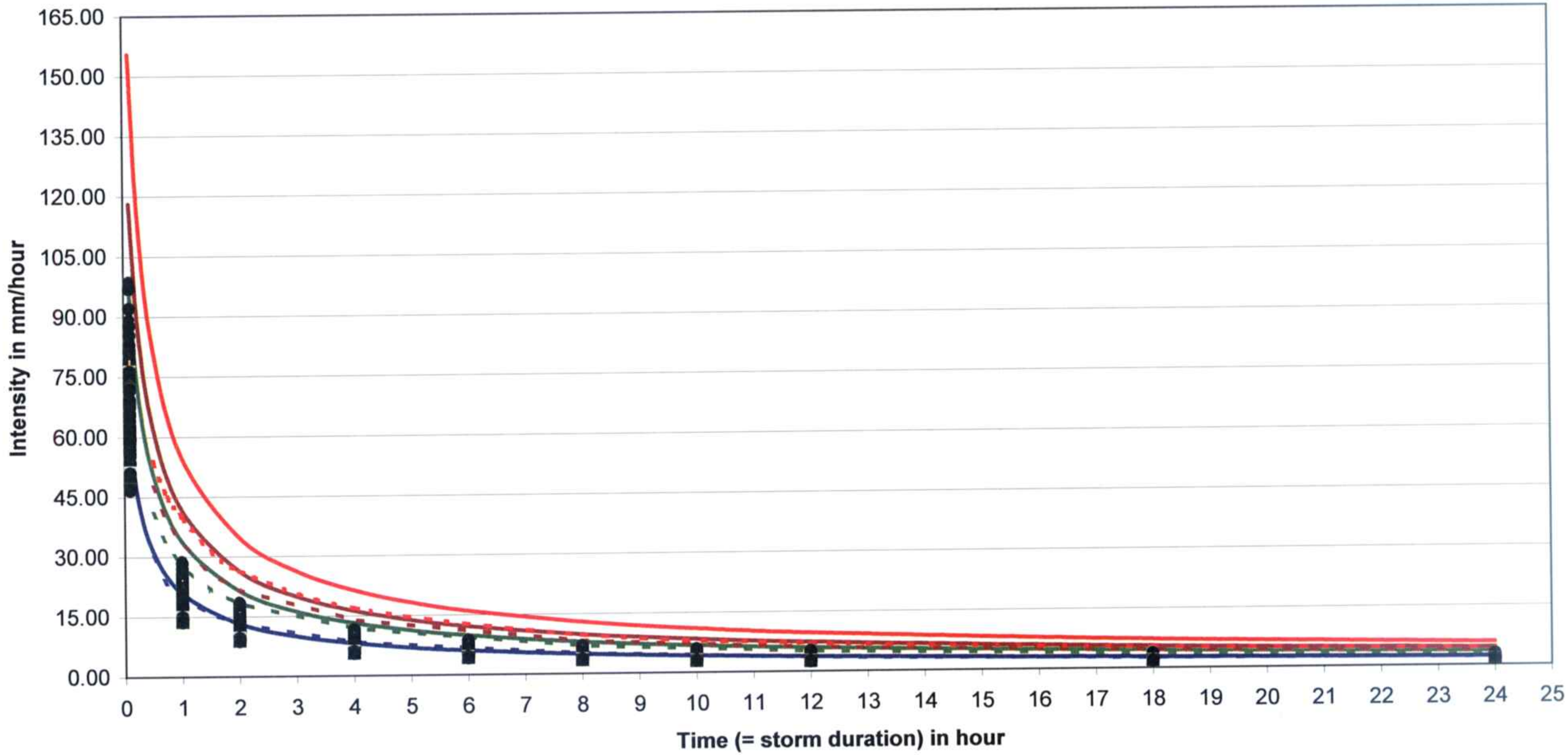


Appendix B3:

IDF curves for Csiro Control data set at Molteno-reservoir

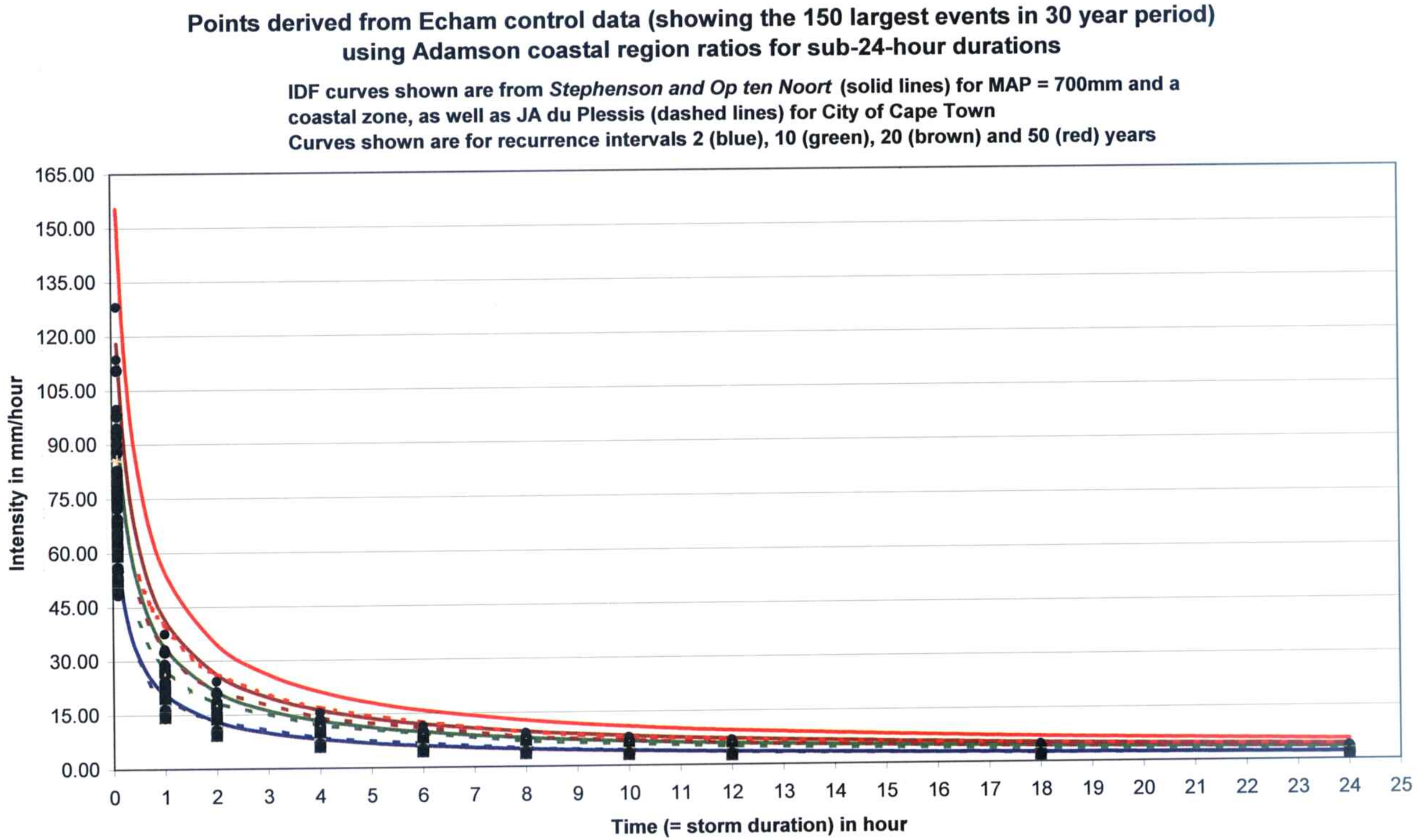
Points derived from Csiro control data (showing the 150 largest events in 30 year period) using Adamson coastal region ratios for sub-24-hour durations

IDF curves shown are from *Stephenson and Op ten Noort* (solid lines) for MAP = 700mm and a coastal zone, as well as JA du Plessis (dashed lines) for City of Cape Town
Curves shown are for recurrence intervals 2 (blue), 10 (green), 20 (brown) and 50 (red) years



Appendix B4:

IDF curves for Echam control data set at Molteno-reservoir

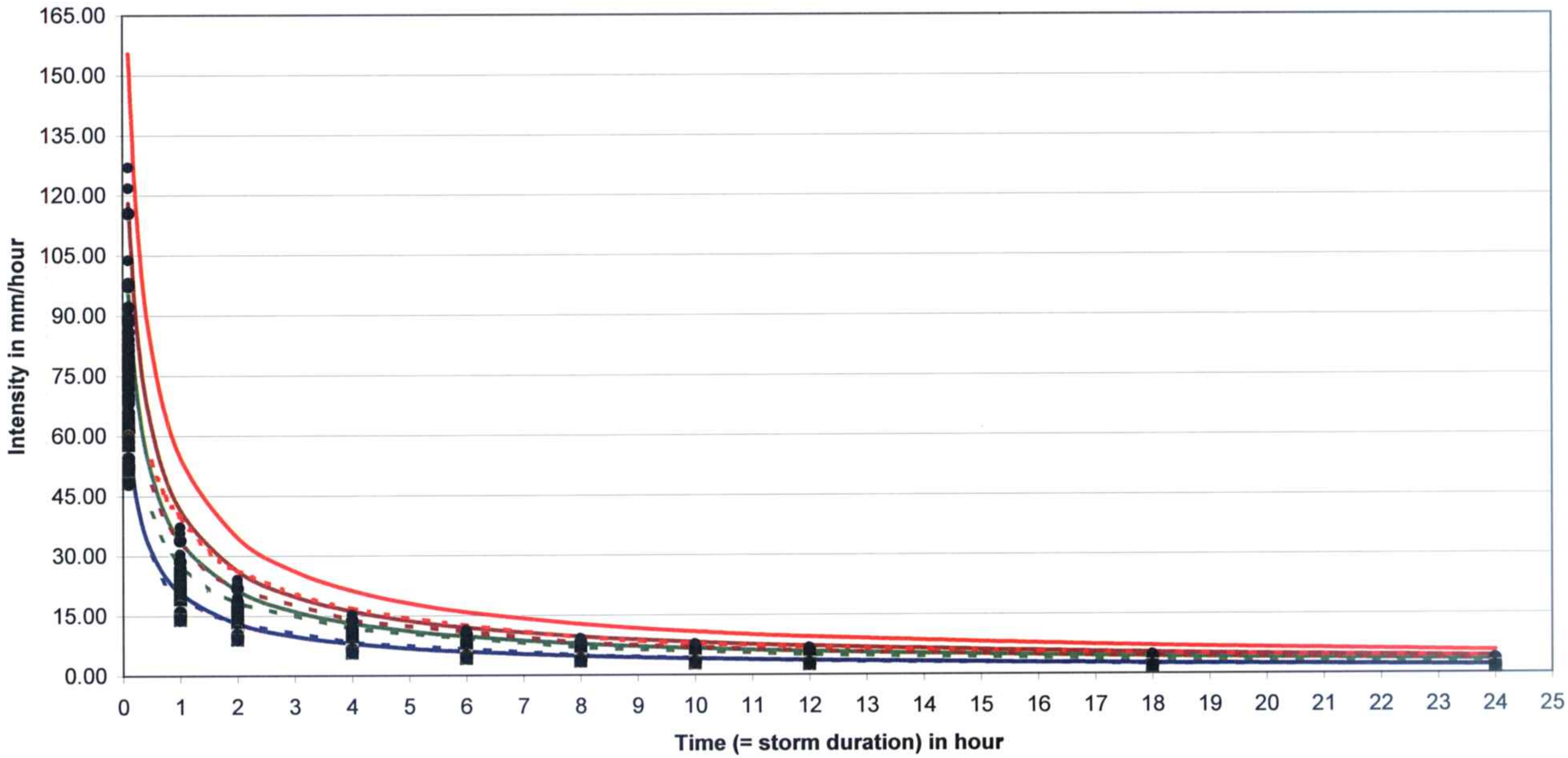

Points derived from Echam control data (showing the 150 largest events in 30 year period) using Adamson coastal region ratios for sub-24-hour durations
IDF curves shown are from Stephenson and Op ten Noort (solid lines) for MAP = 700mm and a coastal zone, as well as JA du Plessis (dashed lines) for City of Cape Town
Curves shown are for recurrence intervals 2 (blue), 10 (green), 20 (brown) and 50 (red) years
Intensity in mm/hour
165.00
150.00
135.00
120.00
105.00
90.00
75.00
60.00
45.00
30.00
15.00
0.00
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25
Time (= storm duration) in hour

Appendix B5:

IDF curves for Hadam control data set at Molteno-reservoir

Points derived from Hadam control data (showing the 150 largest events in 31 year period) using Adamson coastal region ratios for sub-24-hour durations

IDF curves shown are from *Stephenson and Op ten Noort* (solid lines) for MAP = 700mm and a coastal zone, as well as JA du Plessis (dashed lines) for City of Cape Town
Curves shown are for recurrence intervals 2 (blue), 10 (green), 20 (brown) and 50 (red) years

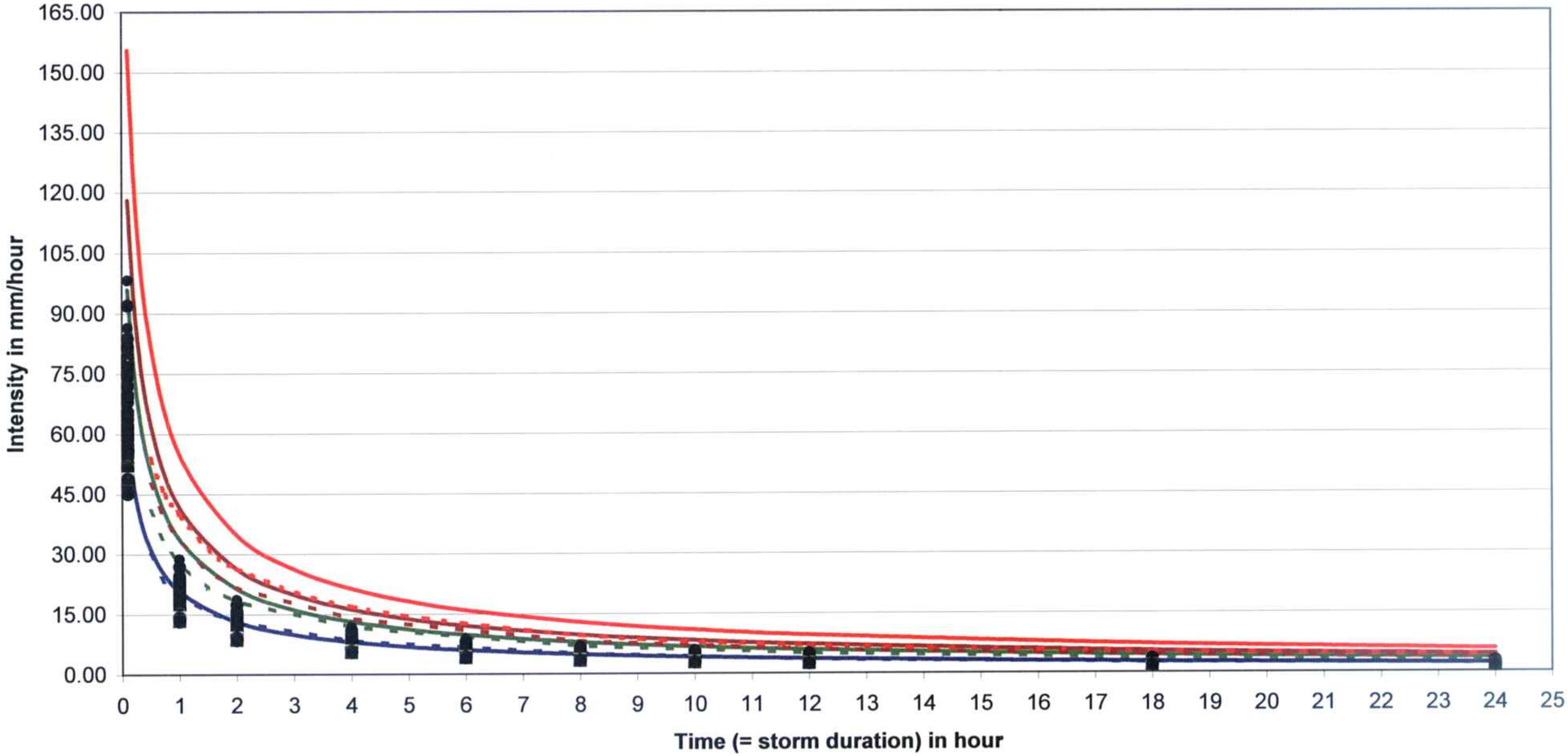


Appendix B6:

IDF curves for Echam future data set at Molteno-reservoir

Points derived from Echam future data (showing the 150 largest events in 30 year period) using Adamson coastal region ratios for sub-24-hour durations

IDF curves shown are from *Stephenson and Op ten Noort* (solid lines) for MAP = 700mm and a coastal zone, as well as JA du Plessis (dashed lines) for City of Cape Town
Curves shown are for recurrence intervals 2 (blue), 10 (green), 20 (brown) and 50 (red) years

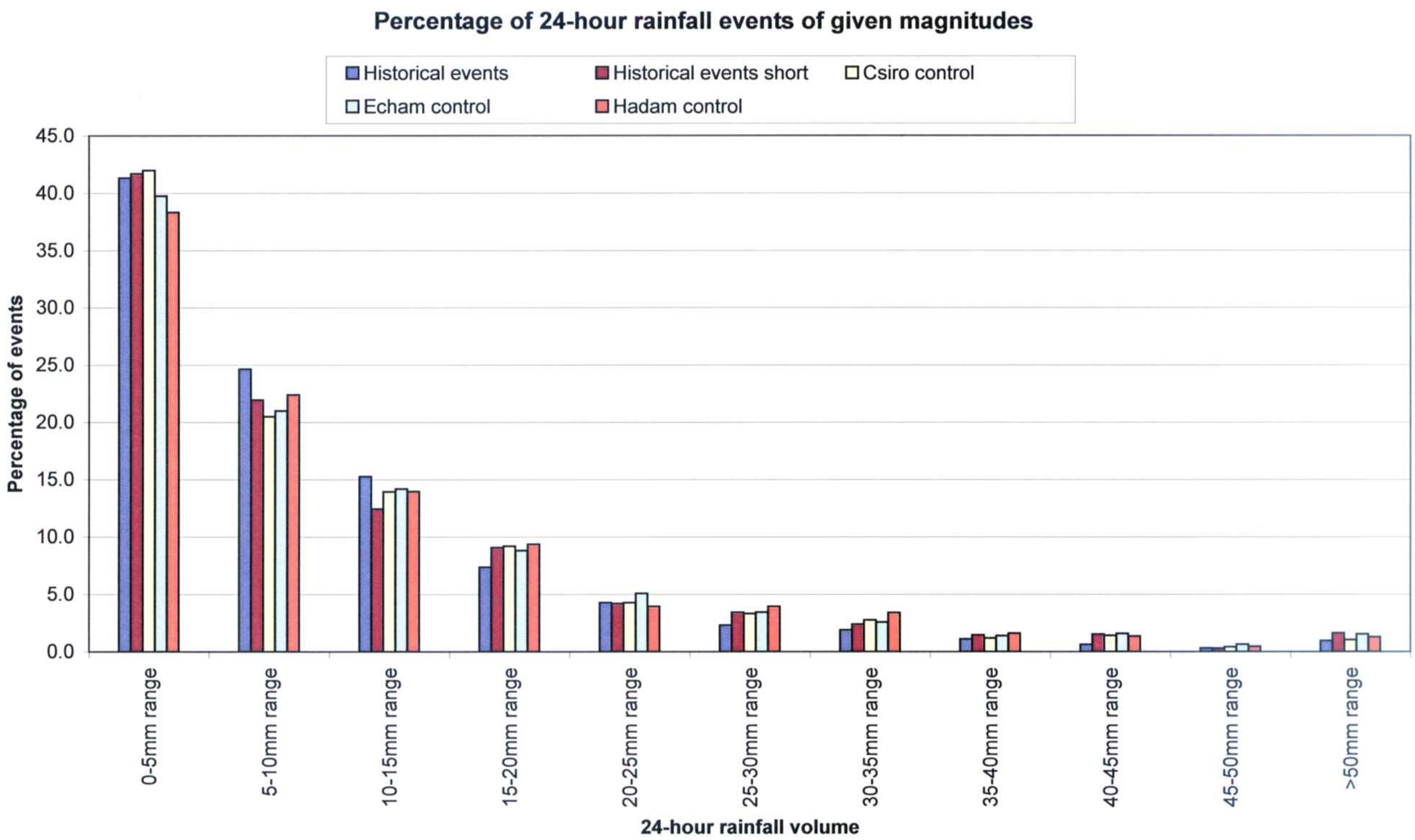


Appendix C:

Analysis of historical, control and forecasted rainfall data on the basis of percentage of occurrence of events of given depths, for City of Cape Town – City Bowl

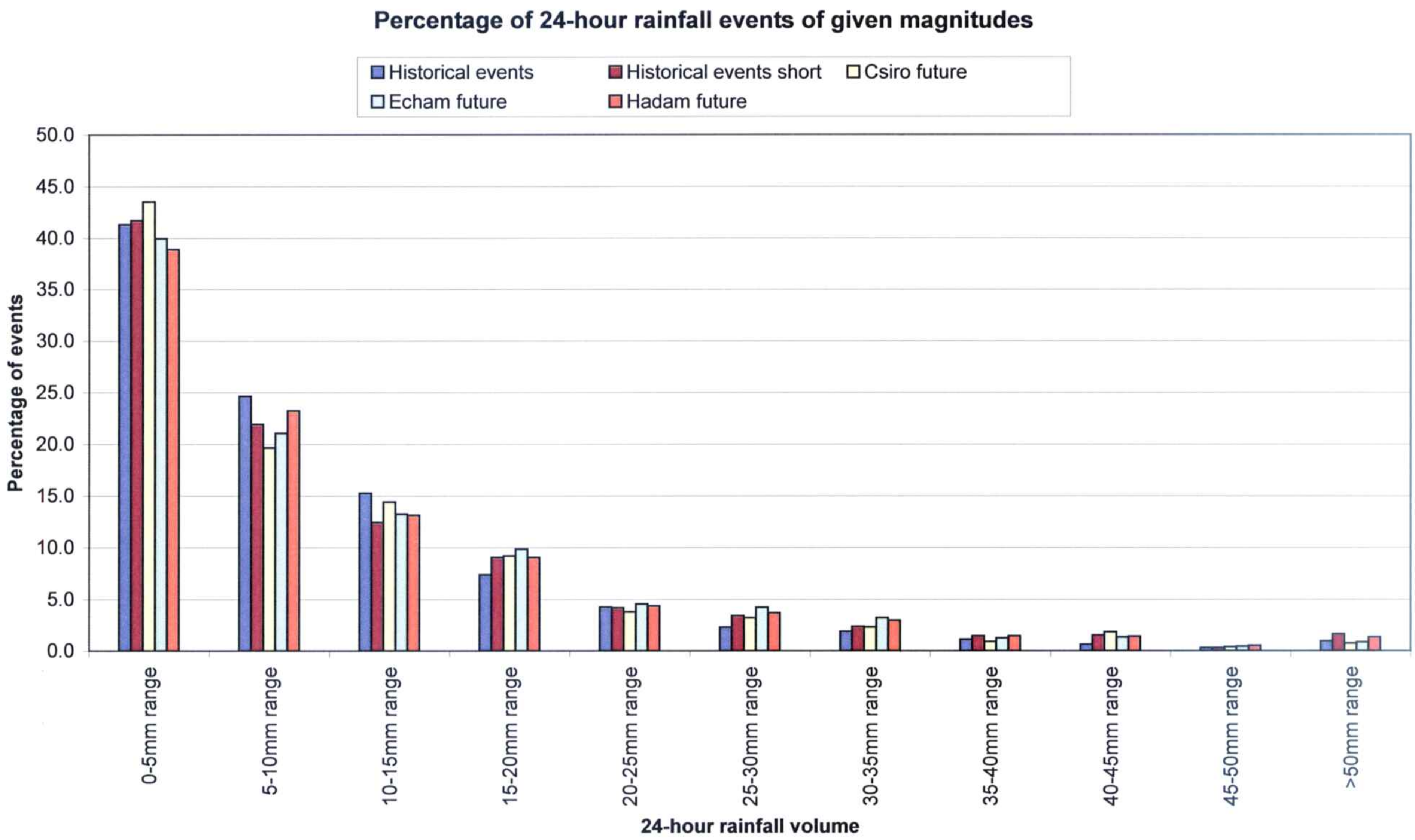
Appendix C1:

Comparison of percentage of occurrence of historical and control data sets at Molteno-reservoir


Percentage of 24-hour rainfall events of given magnitudes
Historical events
Historical events short
Csiro control
Echam control
Hadam control
Percentage of events
45.0
40.0
35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
0-5mm range
5-10mm range
10-15mm range
15-20mm range
20-25mm range
25-30mm range
30-35mm range
35-40mm range
40-45mm range
45-50mm range
>50mm range
24-hour rainfall volume

Appendix C2:

Comparison of percentage of occurrence of historical and future data sets at Molteno-reservoir


Percentage of 24-hour rainfall events of given magnitudes
Historical events
Historical events short
Csiro future
Echam future
Hadam future
Percentage of events
50.0
45.0
40.0
35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
0-5mm range
5-10mm range
10-15mm range
15-20mm range
20-25mm range
25-30mm range
30-35mm range
35-40mm range
40-45mm range
45-50mm range
>50mm range
24-hour rainfall volume

Appendix D:

Detail results of four additional stations

Table of occurrence of normalized data, of different ranges of 24 hour rainfall events for various models.
(Normalized means data has been divided by corresponding History-value)

The table below shows the historical as well as control data

Model	0-5mm range	5-10mm range	10-15mm range	15-20mm range	20-25mm range	25-30mm range	30-35mm range	35-40mm range	40-45mm range	45-50mm range	>50mm range	Average
History short	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	
Csiro control	0.995	0.995	1.011	1.034	1.038	1.061	1.025	0.859	0.816	0.879	0.703	0.947
Echam control	0.914	0.996	1.053	0.997	1.136	1.097	1.294	1.215	0.931	1.120	0.897	1.059
Hadam control	0.924	1.031	1.036	1.044	1.015	1.043	1.218	1.209	0.837	1.039	0.720	1.011

According to the averages, Hadam is the preferred model

Each stations data was firstly nomalized by dividing every value with the corresponding value for the specific station's historical record, as explained in the following example:

Station 4695 Hadam control = 32.41, and Station 4695 History short = 36.13 => Station 4695 Normalized = 32.41/36.13 = 0.897
Station 20714 Hadam control = 46.78 and Station 20714 History short = 48.49 => Station 20714 Normalized = 46.78/48.49 = 0.965
Station 20719 Hadam control = 30.87 and Station 20719 History short = 33.53 => Station 20719 Normalized = 30.87/33.53 = 0.921
Station 20748 Hadam control = 28.68 and Station 20748 History short = 31.30 => Station 20748 Normalized = 28.68/31.30 = 0.916
Station Molteno Hadam control = 38.32 and Station Molteno History short = 41.69 => Station Molteno Normalized = 38.32/41.69 = 0.919

The next step was to regionalize the data, by adding the values together and dividing by 5 (5 stations) =>
0.897 + 0.965 + 0.921 + 0.916 + 0.919 = 4.618 => 4.618 / 5 = 0.924

Individual station results (the data for the stations has not been added together (therefor not regionalized) and also not divided by the historical data (therefor not normalized):

Station 4695

Model	0-5mm range	5-10mm range	10-15mm range	15-20mm range	20-25mm range	25-30mm range	30-35mm range	35-40mm range	40-45mm range	45-50mm range	>50mm range
History short	36.13	21.47	11.32	8.44	6.48	4.45	3.40	2.03	1.83	0.92	3.53
Csiro control	36.12	22.74	10.71	8.09	6.60	4.65	3.27	1.89	1.82	0.81	3.30
Echam control	30.93	22.31	11.83	8.74	6.37	5.24	3.92	2.83	2.52	1.17	4.14
Hadam control	32.41	22.31	12.15	8.86	6.87	4.59	4.17	3.29	1.69	0.98	2.67

Station 20714

Model	0-5mm range	5-10mm range	10-15mm range	15-20mm range	20-25mm range	25-30mm range	30-35mm range	35-40mm range	40-45mm range	45-50mm range	>50mm range
History short	48.49	24.53	10.90	7.32	2.73	2.73	1.43	0.86	0.57	0.14	0.29
Csiro control	47.75	25.05	11.04	9.13	2.72	2.39	1.24	0.53	0.10	0.00	0.05
Echam control	44.06	27.12	11.27	7.87	3.40	2.37	2.73	1.03	0.10	0.00	0.05
Hadam control	46.78	26.61	10.59	8.66	2.76	2.21	1.43	0.83	0.14	0.00	0.00

Station 20719

Model	0-5mm range	5-10mm range	10-15mm range	15-20mm range	20-25mm range	25-30mm range	30-35mm range	35-40mm range	40-45mm range	45-50mm range	>50mm range
History short	33.53	18.00	12.24	9.77	6.41	4.66	3.43	3.28	2.04	1.31	5.32
Csiro control	34.14	17.96	11.62	9.24	6.97	5.74	3.77	2.98	1.94	1.28	4.37
Echam control	31.64	17.26	12.42	8.81	7.46	5.56	3.67	3.64	2.14	1.62	5.77
Hadam control	30.87	18.57	12.02	9.59	6.63	4.42	4.45	3.87	2.35	1.88	5.33

Station 20748

Model	0-5mm range	5-10mm range	10-15mm range	15-20mm range	20-25mm range	25-30mm range	30-35mm range	35-40mm range	40-45mm range	45-50mm range	>50mm range
History short	31.30	19.34	12.81	9.20	6.31	4.49	3.56	2.67	2.71	1.82	5.78
Csiro control	30.21	18.58	13.14	9.24	6.70	5.33	3.69	2.77	2.80	2.02	5.52
Echam control	28.40	17.74	13.24	9.18	6.78	5.58	4.50	3.80	2.75	1.64	6.40
Hadam control	28.68	18.87	13.23	8.96	6.47	5.72	4.08	3.15	2.65	2.09	6.10

Station Molteno

Model	0-5mm range	5-10mm range	10-15mm range	15-20mm range	20-25mm range	25-30mm range	30-35mm range	35-40mm range	40-45mm range	45-50mm range	>50mm range
History	41.31	24.62	15.25	7.37	4.28	2.31	1.89	1.10	0.62	0.31	0.96
History short	41.69	21.92	12.44	9.07	4.19	3.43	2.38	1.45	1.51	0.29	1.63
Csiro control	41.96	20.50	13.93	9.19	4.29	3.32	2.77	1.18	1.42	0.41	1.04
Echam control	39.75	21.00	14.18	8.83	5.09	3.44	2.58	1.38	1.57	0.64	1.53
Hadam control	38.32	22.38	13.96	9.36	3.95	3.95	3.40	1.59	1.35	0.45	1.28

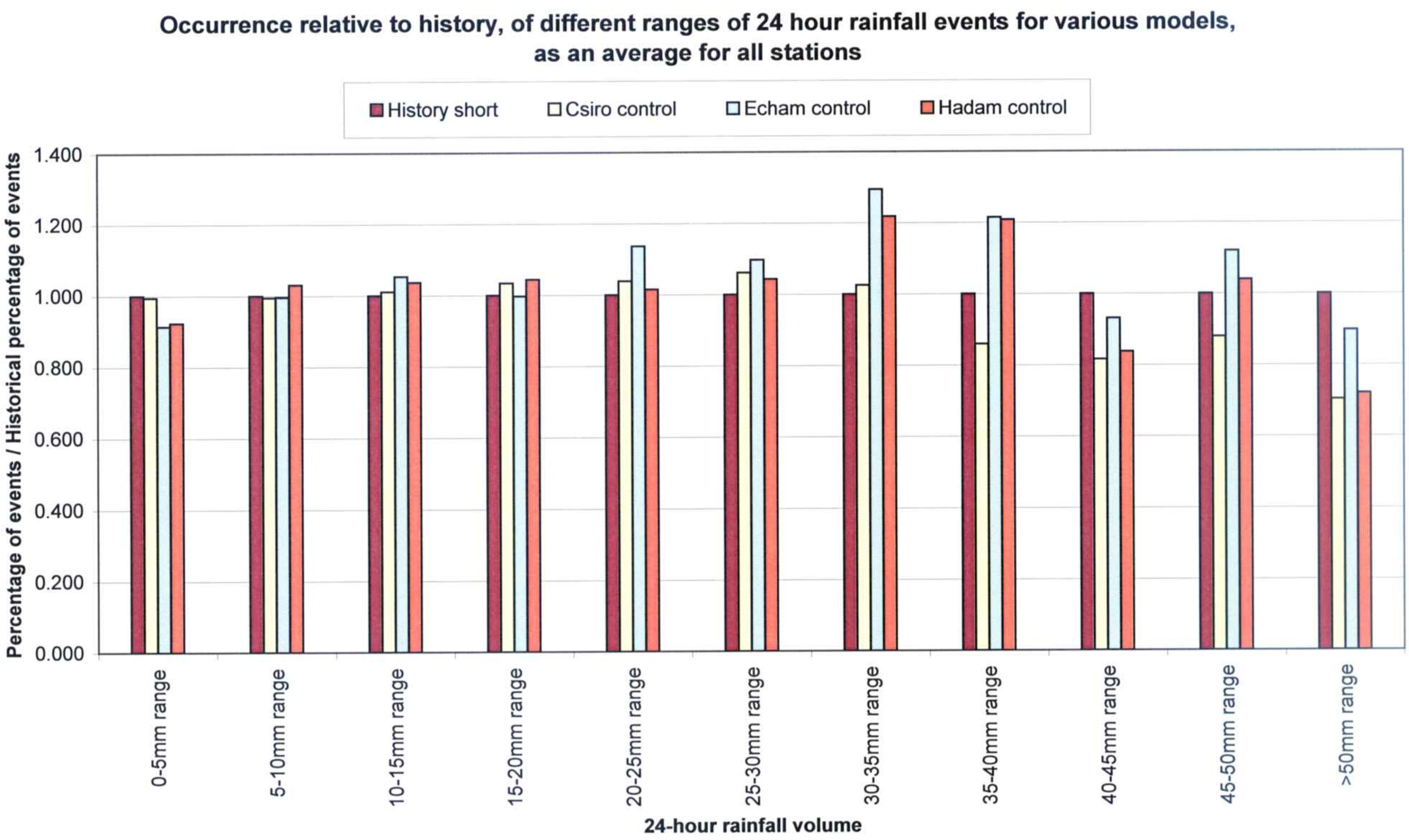

Occurrence relative to history, of different ranges of 24 hour rainfall events for various models, as an average for all stations
History short
Csiro control
Echam control
Hadam control
Percentage of events / Historical percentage of events
1.400
1.200
1.000
0.800
0.600
0.400
0.200
0.000
0-5mm range
5-10mm range
10-15mm range
15-20mm range
20-25mm range
25-30mm range
30-35mm range
35-40mm range
40-45mm range
45-50mm range
>50mm range
24-hour rainfall volume

Table of occurrence of normalized data, of different ranges of 24 hour rainfall events for various models.
(Normalized means data has been divided by corresponding History-value)

The table below shows the historical as well as forecasted data

Model	0-5mm range	5-10mm range	10-15mm range	15-20mm range	20-25mm range	25-30mm range	30-35mm range	35-40mm range	40-45mm range	45-50mm range	>50mm range
History short	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Csiro future	1.026	0.983	1.015	1.050	0.975	0.991	0.977	0.831	0.921	0.875	0.588
Echam future	0.952	0.998	1.051	1.014	1.039	1.157	1.238	1.014	0.851	1.093	0.707
Hadam future	0.955	1.014	0.978	1.002	1.062	1.113	1.155	1.074	0.835	0.961	0.830

Hadam is the preferred model

Hadam's results compare most favourably with that of the regionalized and normalized historical data. One would therefore have the most confidence in the predicted future results of this model. It was however decided to show the results of the other models' forecasted data as well, to underline the general trend forecasted by these models.

Individual station results - The data for the stations has not been added together (therefor not regionalized) and also not divided by the historical data (therefor not normalized):

Station 4695

Model	0-5mm range	5-10mm range	10-15mm range	15-20mm range	20-25mm range	25-30mm range	30-35mm range	35-40mm range	40-45mm range	45-50mm range	>50mm range
History short	36.13	21.47	11.32	8.44	6.48	4.45	3.40	2.03	1.83	0.92	3.53
Csiro future	37.24	21.98	10.51	7.85	6.89	4.46	3.46	2.07	2.23	1.00	2.31
Echam future	34.67	21.82	11.86	7.29	6.81	5.37	3.82	2.27	1.55	1.31	3.22
Hadam future	33.76	21.79	10.20	7.84	8.29	5.78	3.68	2.51	1.80	0.68	3.68

Station 20714

Model	0-5mm range	5-10mm range	10-15mm range	15-20mm range	20-25mm range	25-30mm range	30-35mm range	35-40mm range	40-45mm range	45-50mm range	>50mm range
History short	48.49	24.53	10.90	7.32	2.73	2.73	1.43	0.86	0.57	0.14	0.29
Csiro future	47.75	25.05	11.04	9.13	2.72	2.39	1.24	0.53	0.10	0.00	0.05
Echam future	47.52	22.97	12.37	7.91	2.69	2.74	2.54	1.01	0.20	0.05	0.00
Hadam future	47.81	25.36	11.73	7.80	2.47	2.37	1.46	0.75	0.15	0.05	0.05

Station 20719

Model	0-5mm range	5-10mm range	10-15mm range	15-20mm range	20-25mm range	25-30mm range	30-35mm range	35-40mm range	40-45mm range	45-50mm range	>50mm range
History short	33.53	18.00	12.24	9.77	6.41	4.66	3.43	3.28	2.04	1.31	5.32
Csiro future	35.56	17.53	11.41	10.11	6.12	5.23	3.46	2.94	2.20	1.24	4.21
Echam future	30.51	19.46	12.51	10.00	6.35	5.84	2.92	2.86	2.51	1.21	5.84
Hadam future	32.46	18.36	10.55	9.98	6.99	5.30	4.24	3.44	1.84	1.21	5.63

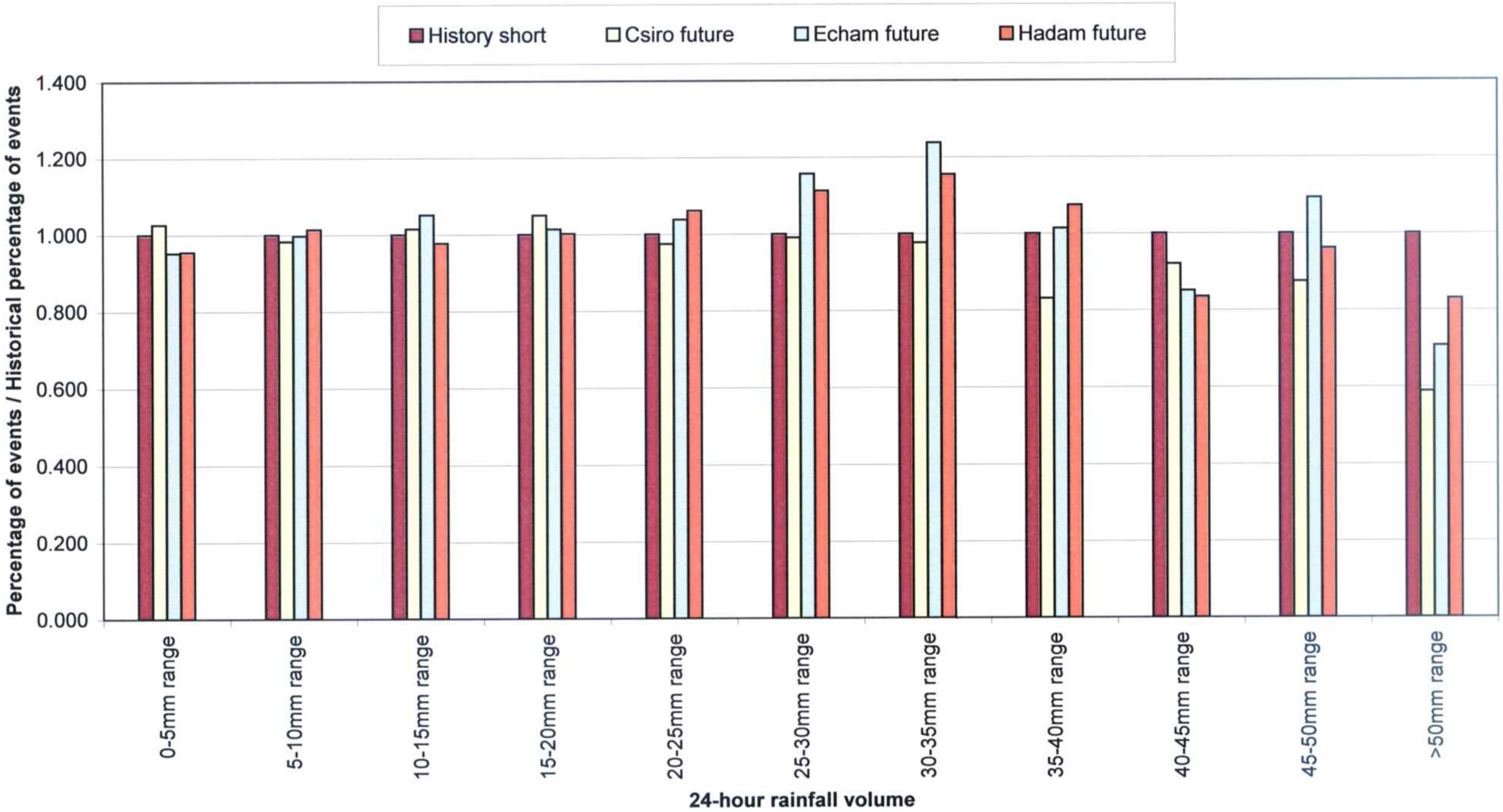
Station 20748

Model	0-5mm range	5-10mm range	10-15mm range	15-20mm range	20-25mm range	25-30mm range	30-35mm range	35-40mm range	40-45mm range	45-50mm range	>50mm range
History short	31.30	19.34	12.81	9.20	6.31	4.49	3.56	2.67	2.71	1.82	5.78
Csiro future	31.63	19.33	13.42	9.44	5.97	4.55	3.62	2.68	2.50	1.81	5.04
Echam future	29.84	19.23	12.66	9.33	6.81	4.87	3.89	2.76	2.56	2.32	5.74
Hadam future	29.84	18.18	12.76	9.15	6.25	5.30	4.25	3.24	2.98	1.91	6.14

Station Molteno

Model	0-5mm range	5-10mm range	10-15mm range	15-20mm range	20-25mm range	25-30mm range	30-35mm range	35-40mm range	40-45mm range	45-50mm range	>50mm range
History	41.31	24.62	15.25	7.37	4.28	2.31	1.89	1.10	0.62	0.31	0.96
History short	41.69	21.92	12.44	9.07	4.19	3.43	2.38	1.45	1.51	0.29	1.63
Csiro future	43.51	19.65	14.39	9.20	3.81	3.22	2.32	0.90	1.85	0.39	0.75
Echam future	39.95	21.05	13.24	9.86	4.56	4.24	3.22	1.26	1.34	0.43	0.86
Hadam future	38.88	23.22	13.11	9.06	4.37	3.71	2.97	1.44	1.41	0.51	1.33

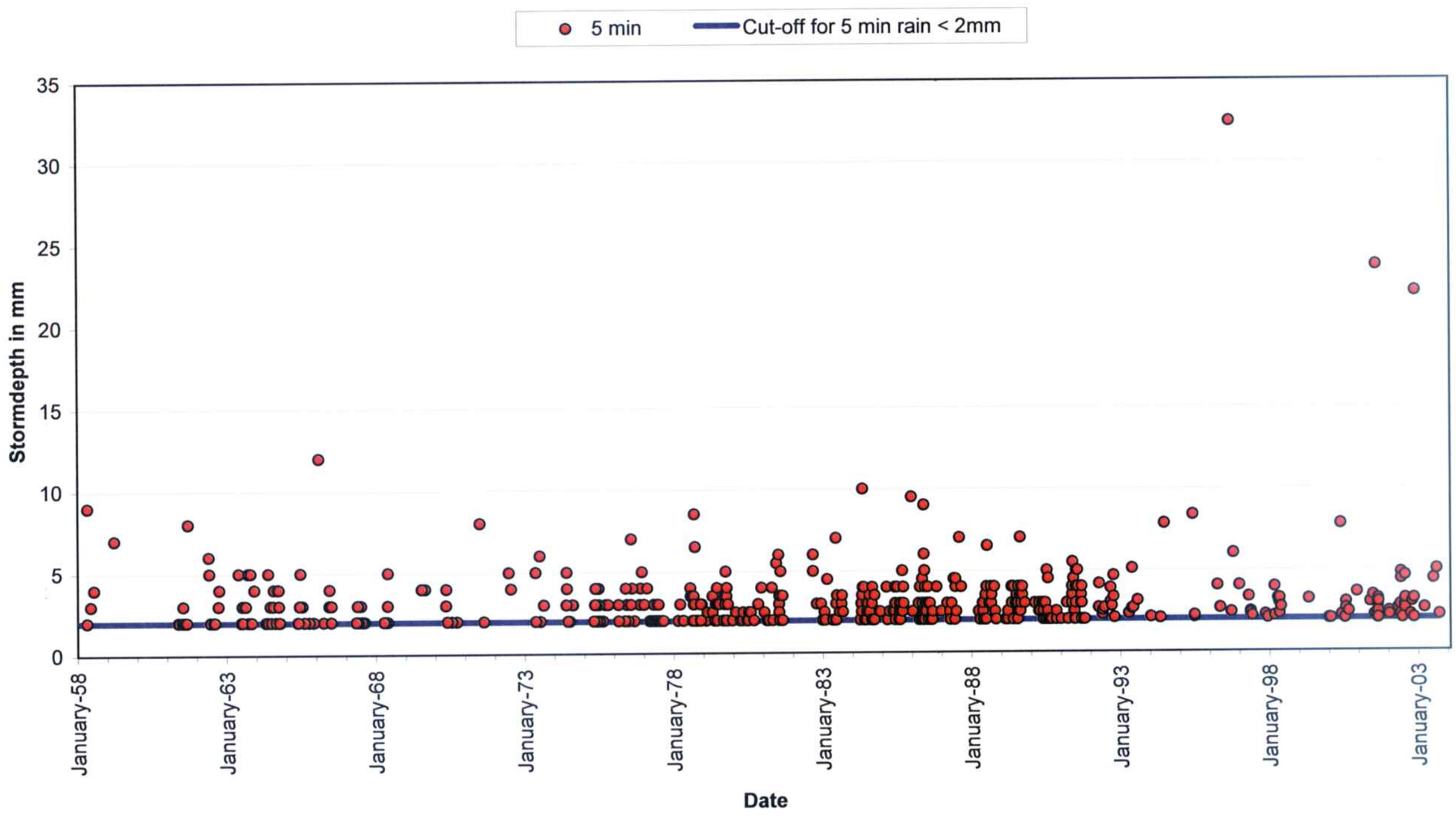
Occurrence relative to history, of different ranges of 24 hour rainfall events for various models, as an average for all stations



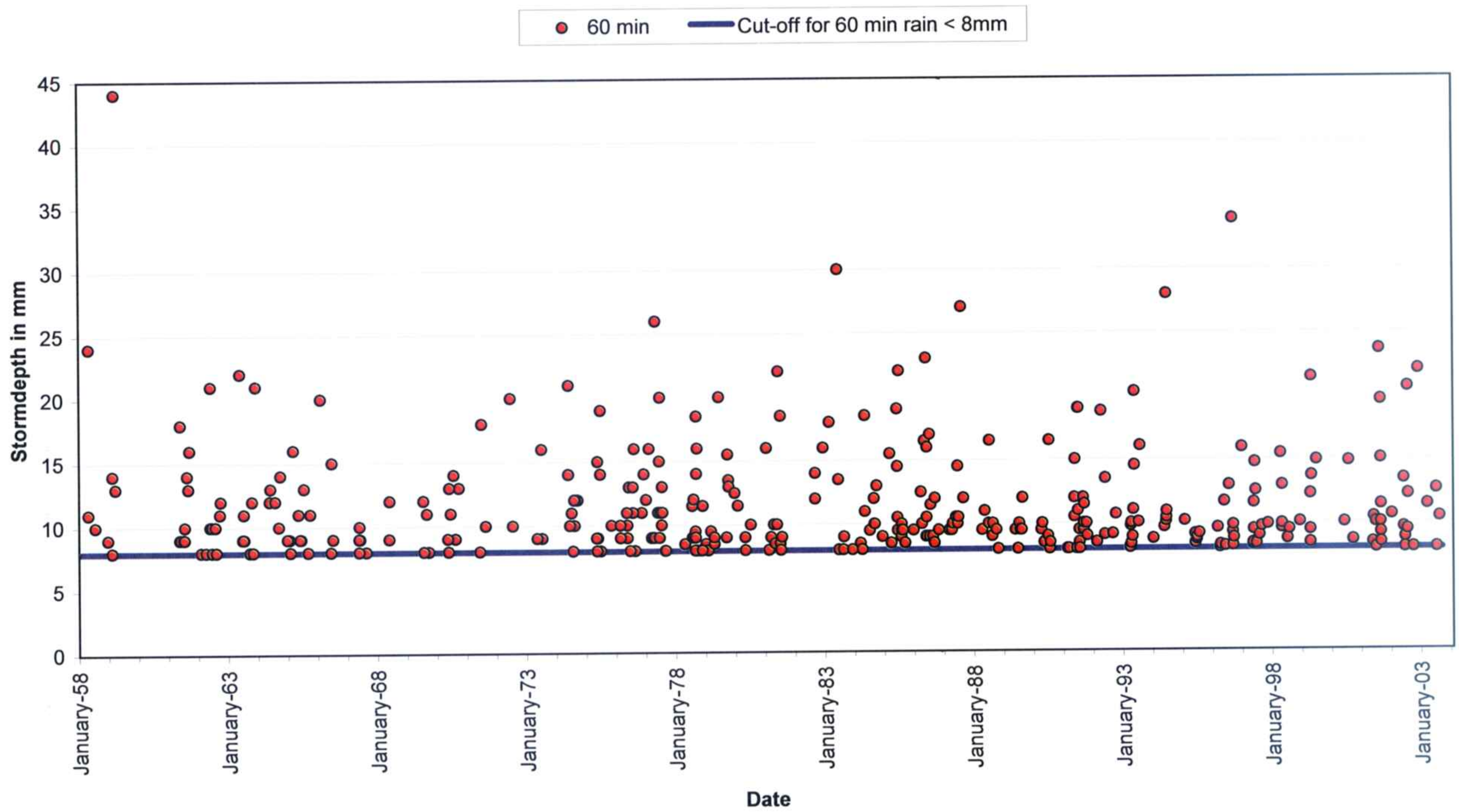
Appendix E:

Detail results of the analysis of each and every storm at Molteno

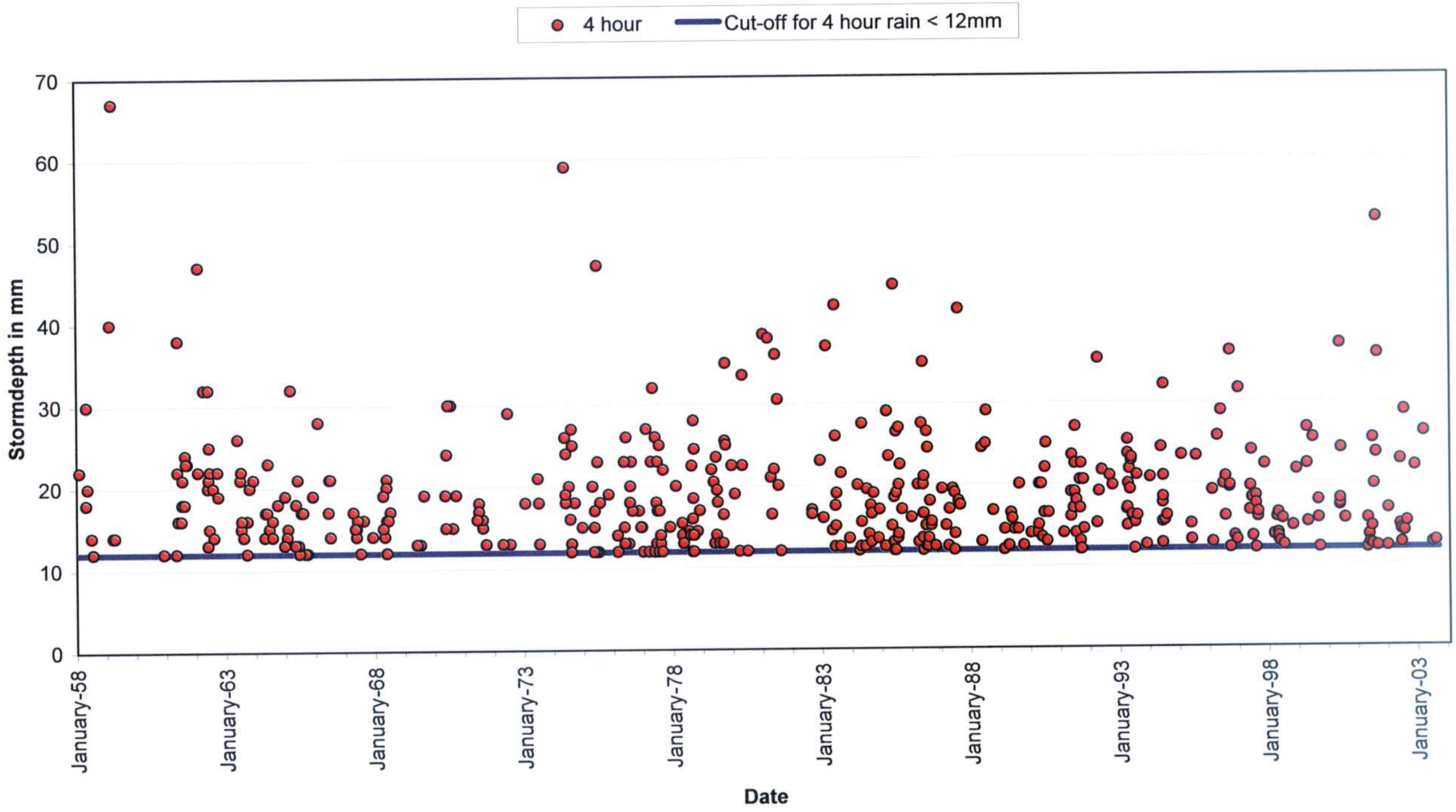
All storms above pre-defined cut-off minimum for 5 minute storm duration for period 1958 to 2003

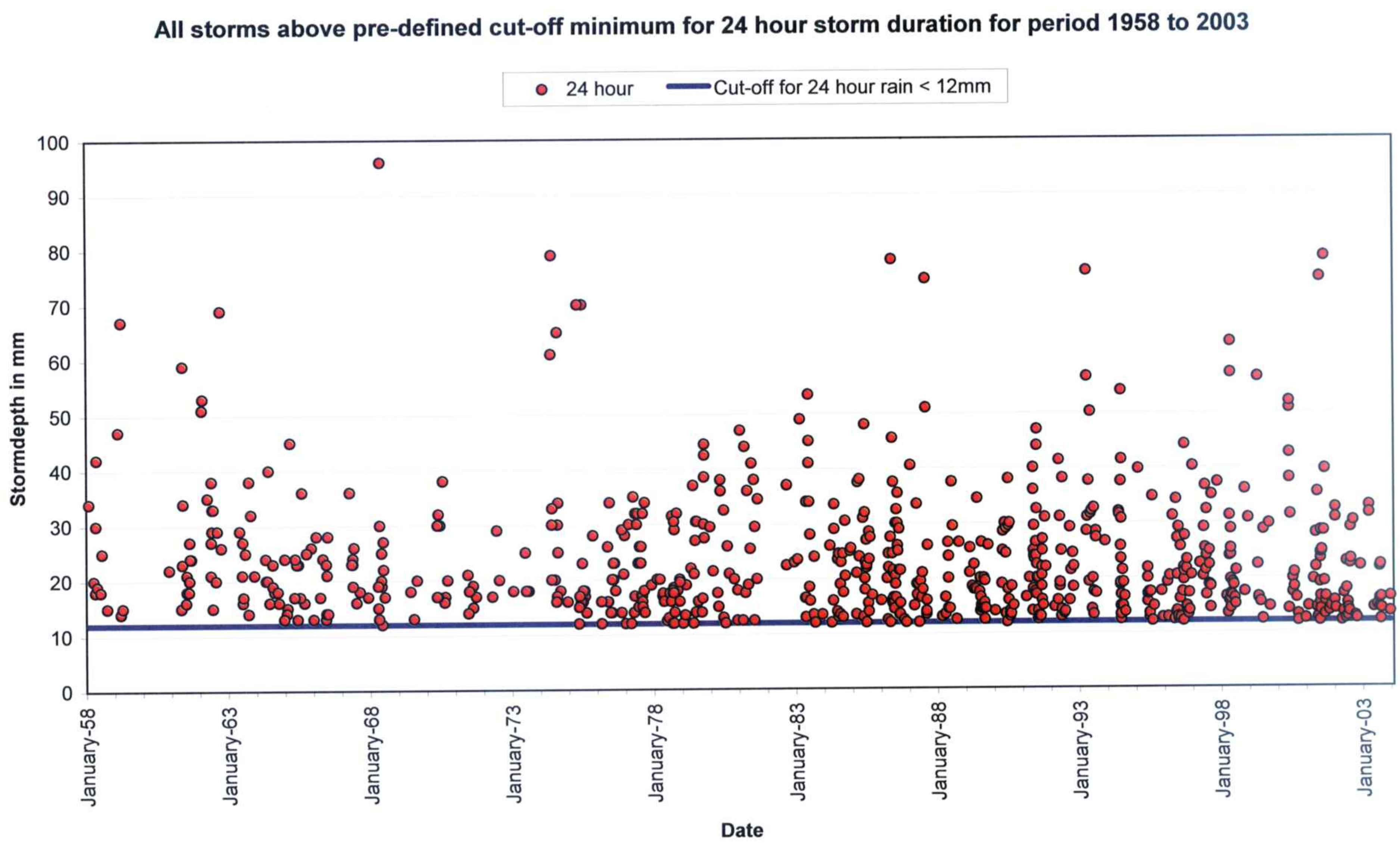


All storms above pre-defined cut-off minimum for 60 minute storm duration for period 1958 to 2003

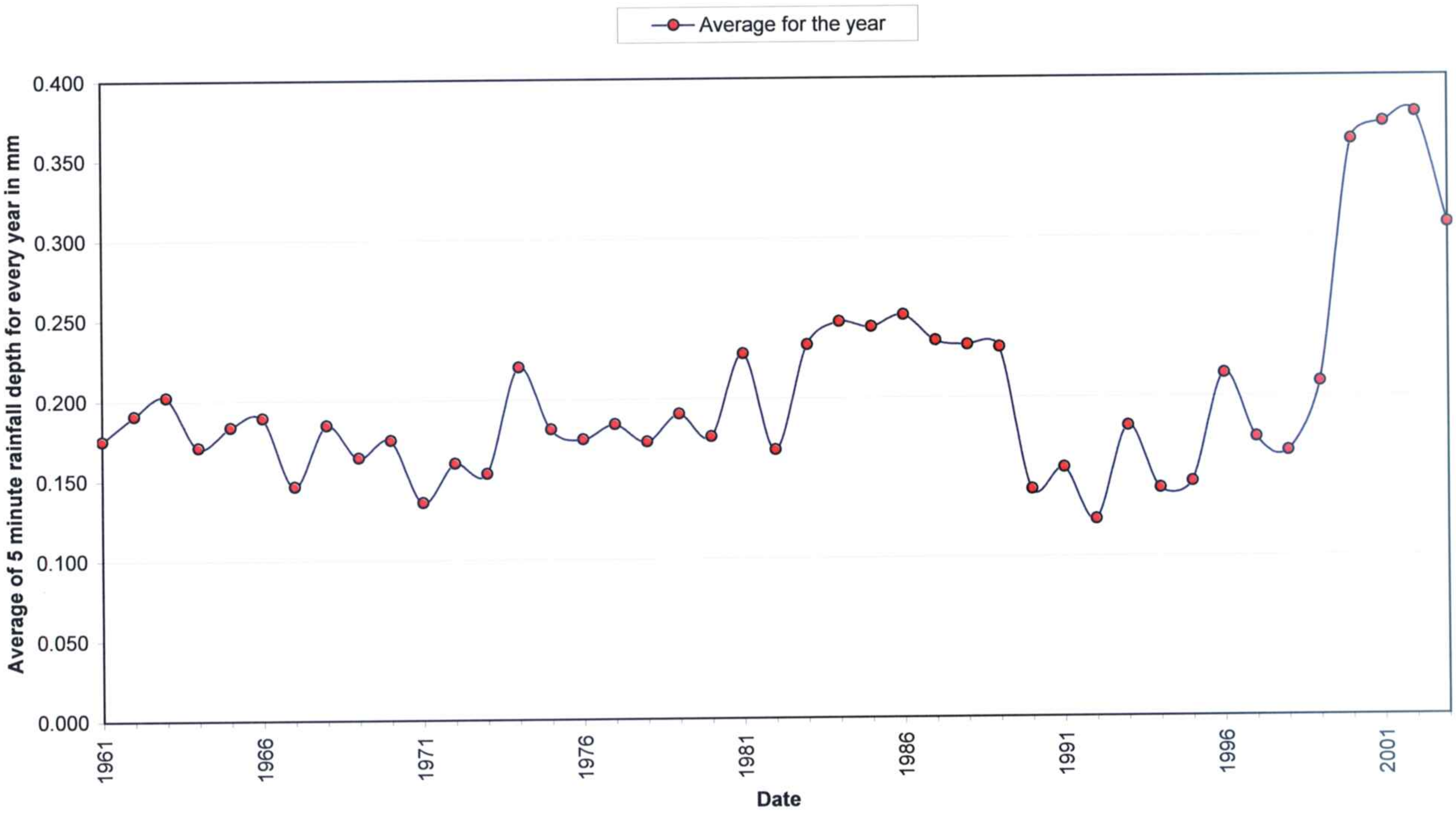


All storms above pre-defined cut-off minimum for 4 hour storm duration for period 1958 to 2003

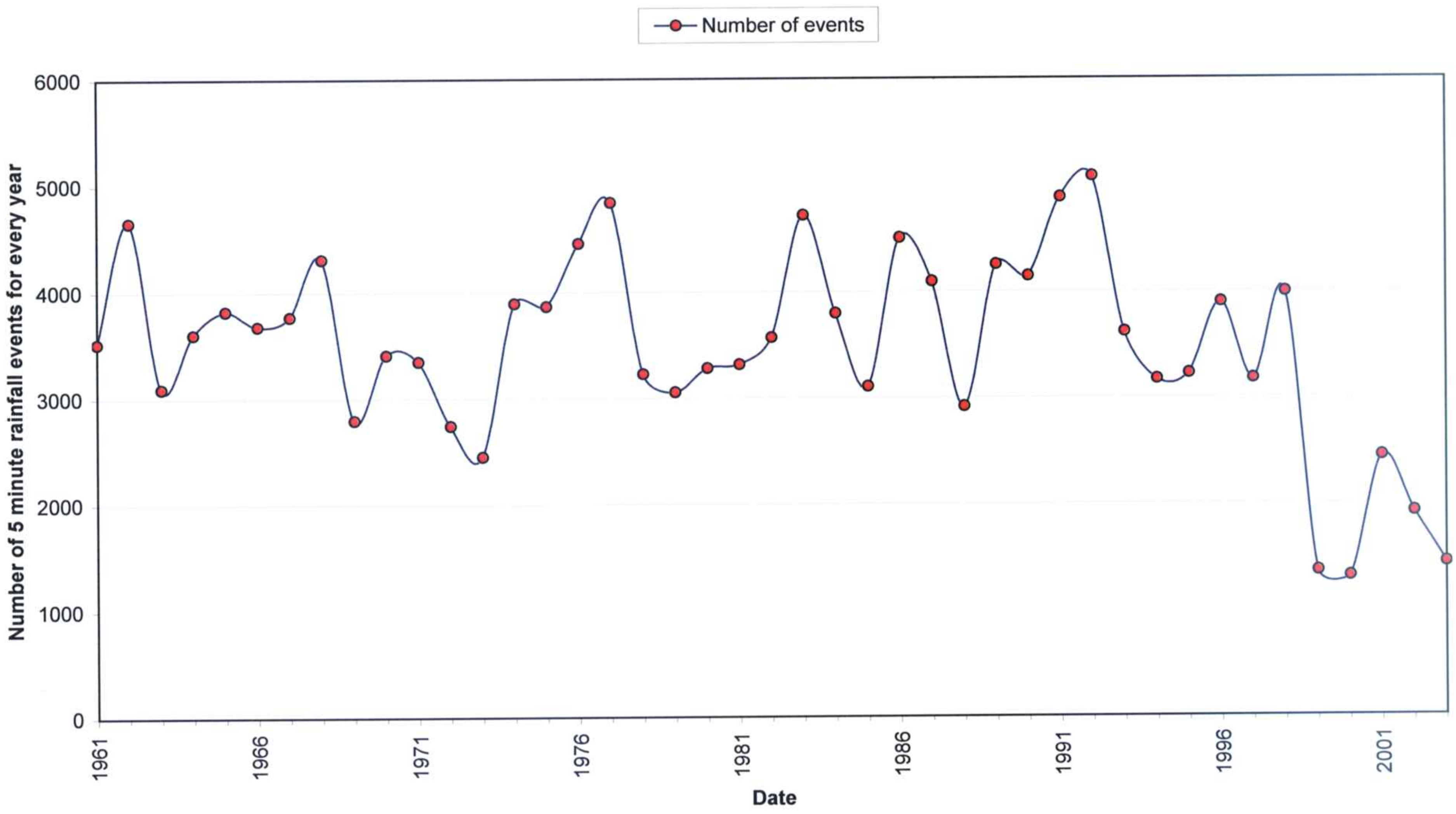



All storms above pre-defined cut-off minimum for 24 hour storm duration for period 1958 to 2003
24 hour
Cut-off for 24 hour rain < 12mm
Stormdepth in mm
100
90
80
70
60
50
40
30
20
10
0
January-58
January-63
January-68
January-73
January-78
January-83
January-88
January-93
January-98
January-03
Date

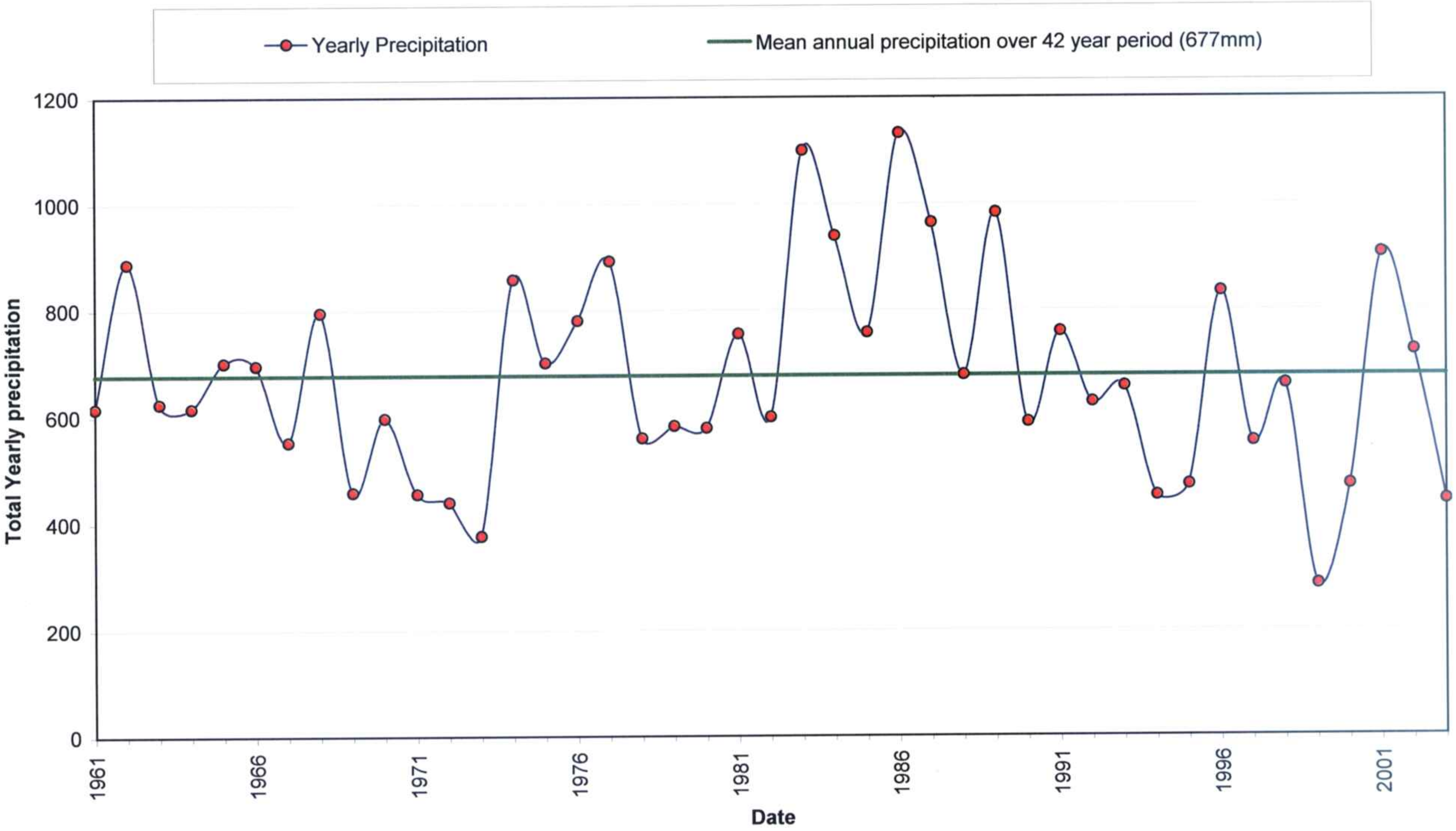
Graph showing the average of the 5 minute duration rainfall depth for every year at Molteno.

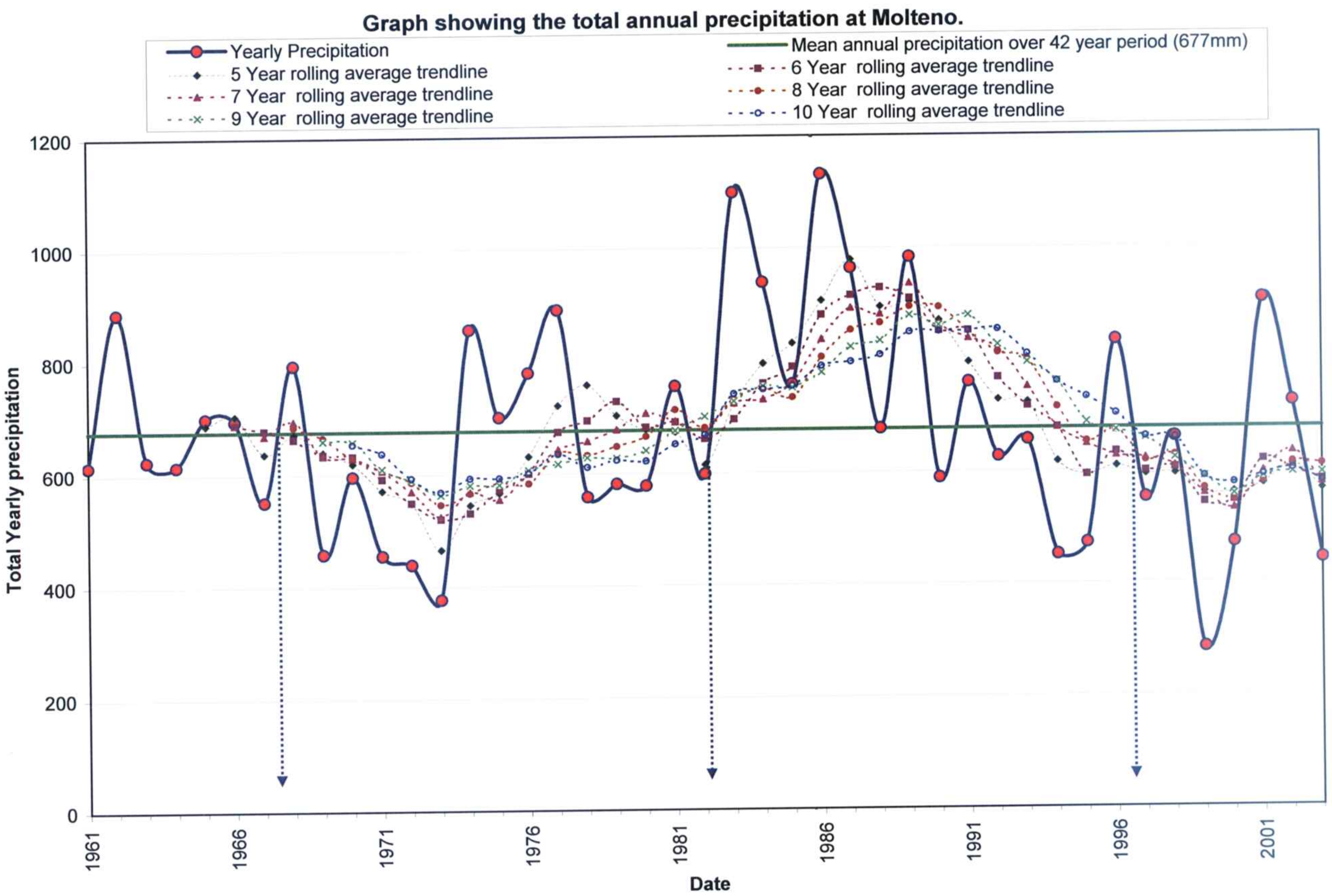


Graph showing the number of the 5 minute duration rainfall events for every year at Molteno.



Graph showing the total annual precipitation at Molteno.





Graph showing the total annual precipitation at Molteno.
Yearly Precipitation
5 Year rolling average trendline
7 Year rolling average trendline
9 Year rolling average trendline
Mean annual precipitation over 42 year period (677mm)
6 Year rolling average trendline
8 Year rolling average trendline
10 Year rolling average trendline
Total Yearly precipitation
1200
1000
800
600
400
200
0
1961
1966
1971
1976
1981
1986
1991
1996
2001
Date