

Future freshwater availability in Cape Town

The impact of Climate Change on annual precipitation in the Cape area.



Bachelor's thesis

Human Geography and Urban and Regional Planning

Student: Thom Horlings

Student Number: S3416801

Coördinator: G. Mallon

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Abstract

From 2015 to 2018, Cape Town, South Africa experienced serious drought resulting in a water crisis. A combination of increased water demand, population growth and a large dependency on surface water makes the Cape Town water systems vulnerable for long periods of decreased precipitation. 96% of all freshwater for the city is coming from a network of dams, all dependent on precipitation in the winter period to replenish. This research focuses on calculating the future fresh water supply for Cape Town by working out the implications of various climate scenarios on the precipitation in Cape Town and translating these predictions to the actual supply of freshwater in the dam reservoirs. A combination of secondary data sources has been used for this study. An analysis on both dam levels and precipitation showed the relation between precipitation and dam levels. Future precipitation for various climate change scenarios has been calculated and show a decrease of precipitation for each scenario, supporting the findings of other researches and predictions. The precipitation predictions have been used to calculate possible future dam levels under the scenarios. The decrease of precipitation results in a decrease of dam levels, and thus the freshwater availability. This shows that Cape Town will need to diversify its water sources in order to be able to keep up with the growing demand and be more resilient to periods with decreased precipitation or extreme weather events.

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1 Introduction

1.1 Background

The dams that supply freshwater to the city of Cape Town dropped to 21% of their capacity in May 2018. The final 10% is difficult to extract for human consumption (Natalie et al, 2019). Therefore, the city developed a plan which would come into place if the capacity dropped further to 13.5%, this scenario is referred to as 'Day Zero' or 'The day that the taps run dry'. The plan included centralized distribution points where citizens could collect 25 liters per day (Natalie et al., 2019; Millington & Scheba, 2021). Day Zero has been averted due to strict water usage restrictions (Mahr, 2018) and early winter rains (Natalie et al., 2019). The water use was restricted to 50 liters per person (Holder & Kommenda, 2018; Sousa et al, 2018). To achieve this Capetonians had to reuse their shower water, limit their toilet flushes and recycle water from their washing machines (Mahr, 2018). The drinking water of Cape Town is mainly coming from dam reservoirs located in the near proximity of the city (City of Cape Town, 2018). Due to longer droughts and an increasing population the city of Cape Town is facing difficulties in supplying enough fresh drinking water (Wilson, 2018). The water scarcity reached its peak in the summer of 2018, after a 3-year period of decreased precipitation (Otto et al., 2018). The economic consequences of this drought are estimated at 400 million US dollar in agriculture losses, 30.000 job losses and a 13-20% decrease in exports (OECD, 2021).

Cape Town is highly dependent on surface water sources for its water supply. Precipitation is collected in various dam reservoirs in and around Cape Town. These reservoirs rely mostly on precipitation in the winter period to replenish and provide the city with freshwater in the dry summer months (City of Cape Town, 2020). This large dependency on rainfall becomes increasingly a problem for Cape Town due to the expected decrease in precipitation. Climate change will impact weather patterns all over the world, including precipitation patterns (IPCC, 2015). The impact of climate changes on weather patterns varies for each location, natural factors and the intensity of climate change. For the Cape Town area a decrease in precipitation has been predicted (Trenberth, 2011; IPCC, 2017). Changes in precipitation patterns will affect the freshwater availability for many regions in the world (Jackson et al., 2001). Research is necessary to predict the implications and prepare accordingly.

1.2 Research Problem

The aim of the research is to investigate the impact of climate change on the freshwater availability of Cape Town. Cape town is highly dependent on winter rainfall that is stored in a network of 14 dam reservoirs. These dams are Cape Town's main source for freshwater, since they are responsible for 98% of Cape Town's water supply (City of Cape Town, 2020). A change in precipitation will therefore have a large influence on the water availability. The relation between precipitation and water levels in the dam reservoirs will be investigated, this relation will be used to predict future dam levels by looking at the predictions for precipitation patterns in the specific area. Since the climate predictions are still highly uncertain the four climate scenarios from the IPCC (2015, 2017) will be used, this allows to investigate the effects of climate change, while implementing the uncertainty of climate change in the research.

The findings will help understand the relation between precipitation and actual catchment of rainwater in the reservoirs and will help predict future water availability from precipitation in the Cape Town area. The following main research question has been formulated:

What impact does a change in precipitation patterns have on the future freshwater availability of Cape Town, South Africa?

To answer the main research question the following sub questions have been formulated:

1. What is the relation between historic precipitation and dam levels?
2. What is the expected effect of various climate change scenarios on precipitation patterns?
3. What is the expected future freshwater availability in Cape Town?

1.3 Structure

This paper has five chapters. In chapter one the topic is introduced, the aim of the research is explained, and the research problem is defined. Chapter two includes the theoretical framework in which the main concepts are defined. Furthermore, the conceptual model and expected results are positioned here. Chapter three contains the methodology, where the data collection and research methods are explained. The results are presented in chapter four. Chapter five contains the conclusions, future research suggestions and limitations, in this section the results and theory will be combined in order to answer the research questions.

2 Theoretical framework

2.1 Literature review

Precipitation is a part of the water cycle, precipitation consists of evaporated water from the oceans and water transpired from plants and soil (Jackson et al., 2001). Trenberth (2011) explains the hydrological cycle as water that is evaporated by the sun's radiation, which is then moved by wind, forms clouds and eventually falls back on the earth's surface as rain or snow. The water will then find its way back to the oceans through rivers, completing the cycle. In South Africa most precipitation falls in the form of rain (Cape Town, 2019). Most of South Africa receives summer rainfall, whereas Cape Town receives most of its rainfall in the winter months. Primarily due to cold fronts tracking eastwards across the South Atlantic (Natalie et al., 2019). This rainwater is collected in a network of 14 dams, with a collective capacity of around 900.000 ML, however most of this capacity comes from the six largest dams located outside the city itself. The catchment areas of these dams are the mountainous areas outside the city where rainfall is higher than in Cape Town itself (City of Cape Town, 2018).

Otto et al. (2018) investigated the 2015-2018 water shortage to find out the causes and the change of reoccurrence. They found evidence that a lack of precipitation in the catchment areas was the key variable in the historic droughts. Furthermore, they established that the drought was a very rare event, but climate change has significantly increased the chance of prolonged droughts to occur in the future. Climate change will influence the water cycle and precipitation patterns, mainly increasing the extremes (Trenberth, 2011). Human-induced environmental change has its impact on the hydrological cycle, and the use of water as a resource. However, the hydrological change can have different impacts in varying areas (Arnell, 2014). Changes in precipitation and evaporation aspects of the water cycle will directly influence the freshwater availability of Cape Town since the city is largely dependent on the freshwater reservoirs for its drinking water supply. A projected decrease in precipitation and an increase in evaporation for the Cape Town area will decrease the supply of drinking water from the dams, resulting in the need for Cape Town to control demand carefully and diversify its water supply sources (City of Cape Town, 2018; Ziervogel, 2018).

The Earth's climate has been changing throughout history, mainly due to variations in the Earth's orbit that dictate the amount of solar energy our planet receives (NASA, n.d.). However, the current trend of global warming is extremely likely to be caused by human activity at a much faster pace than ever recorded. An important indicator is the amount of carbon dioxide in the atmosphere, currently exceeding 400 parts per million (IPCC, 2015). The Intergovernmental Panel on Climate Change (IPCC) has been studying the changing climate since 1988 and published several influential reports on this topic. Four scenarios for global temperature increase have been made based on a set of variables including population, economic growth and carbon use (Raftery et al., 2017; IPCC, 2015). These scenarios are called Representative Concentration Pathways (RCP) and include a stringent scenario (RCP2.6), two moderate scenarios (RCP4.0 and RCP6.0) and one scenario with very high GHG emissions (RCP8.5) (IPCC, 2015). These scenarios are used to predict the effects of global warming on various natural processes such as surface temperature, sea ice, sea level and acidity of the oceans.

In 2015, 196 countries signed the Paris Agreement, an international treaty that binds the countries to put efforts to limit global warming by as much as 2 degrees celsius, while aiming for 1,5 degrees, compared to pre-industrial levels (Rogelj et al., 2016). The degree to which these countries will succeed in the reduction of their greenhouse gas emissions will largely determine which of the IPCC's RCP scenarios will become reality. A global increase of temperature will affect natural processes like precipitation patterns. However, these changes will not be uniform for all areas (Arnell, 2014). Precipitation is likely to increase in higher latitudes, while mid-latitude and subtropical dry regions precipitation will likely decrease (Trenberth, 2011; IPCC, 2015). For the Cape Town areas specifically, a decrease of precipitation is projected (IPCC, 2013; IPCC 2017). Whereas precipitation changes are sometimes predicted differently by various models, a decrease of precipitation is shown in over 90% of the models of Dosio et al. (2019). The actual consequences of global warming on precipitation will depend on the actual increase of greenhouse gasses in the atmosphere.

Sousa et al. (2018) concluded that severe events like the South African 2015-2018 drought can be expected to occur more often in the future. They also stated that even though dam levels have recovered from the drought the situation remains critical as water use continuously needs to be monitored. It should be remembered that change in precipitation is not the only variable regarding water scarcity, the growing population and increasing water use also pressures water demand (Sousa et al., 2018). Furthermore, Cape Town is a highly unequal city and water scarcity is a day-to-day reality for many lower-class Capetonians; concern is that the pressing climate crisis will further increase these existing inequalities (Millington & Sheba, 2021). Informal settlements often lack good water availability as residents have to stand in line at standpipes for water (Ziervogel, 2018), this reflects in the water consumption as informal settlements use 3.6% of the total water consumption while formal settlements consume 64.5% (Parks et al., 2019).

2.2 Conceptual model

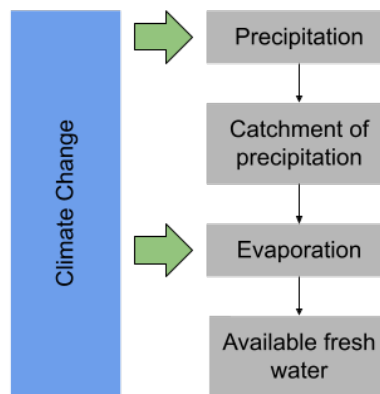


Figure 1. Conceptual model

As seen in figure 1, a simplified version of the freshwater supply in Cape Town is represented. Precipitation in the catchment areas will make its way to the dam reservoirs. In these reservoirs it will be subject to evaporation which slowly reduces the total amount of water in the reservoirs. The total amount of water in the dam reservoirs is not the total amount of freshwater available for use at any specific moment, since the last 10% can hardly be extracted with the current infrastructure (Natalie et al, 2019). Climate change will most certainly affect the precipitation patterns and evaporation, and therefore influencing the availability of freshwater. This research will focus on the effects of climate change on the precipitation in the Cape Town area, and its direct impact on the freshwater availability. The effect of climate change on evaporation is not a focus of the study and will therefore not be discussed extensively, however it should be reminded that global warming will likely increase the evaporation and therefore influence the freshwater supply as well.

2.3 Expected results

It is expected that there will be a relationship between precipitation and the water levels in the dam reservoirs. Also, it is expected that annual precipitation will decrease in the Cape Town area, and that this is correlated with global warming as the IPCC (2015, 2017) suggests. Furthermore, this decrease in precipitation will most likely result in lower dam levels and less freshwater in the future since we expect the precipitation to be correlated with the dam water levels.

3 Methodology

For this research secondary data has been analyzed. The main data that was used are the historic dam levels from the City of Cape Town Open Data Portal, historic precipitation records of the Cape Town area retrieved from NASA, and predictions in precipitation patterns from the IPCC. Lastly spatial data on the dam areas will be needed for the analysis. Secondary data was used since the gathering of primary data is beyond the possibilities of this thesis, since climatic data needs to be collected over a longer period of time and requires specific tools. Since all data is secondary climate data is does not contain any personal information or other ethical sensitive data. The main ethical consideration is to reference all data sources correctly.

Firstly, a profile of the daily water levels in the dam reservoirs has been made. This dataset is coming from the City of Cape Town Open Data Portal and has daily data on all 14 dams from 2012 onwards. The profile exists out of a graph of the dam levels of the six largest dams combined and a graph showing the dam levels separately to allow for comparison between the dams.

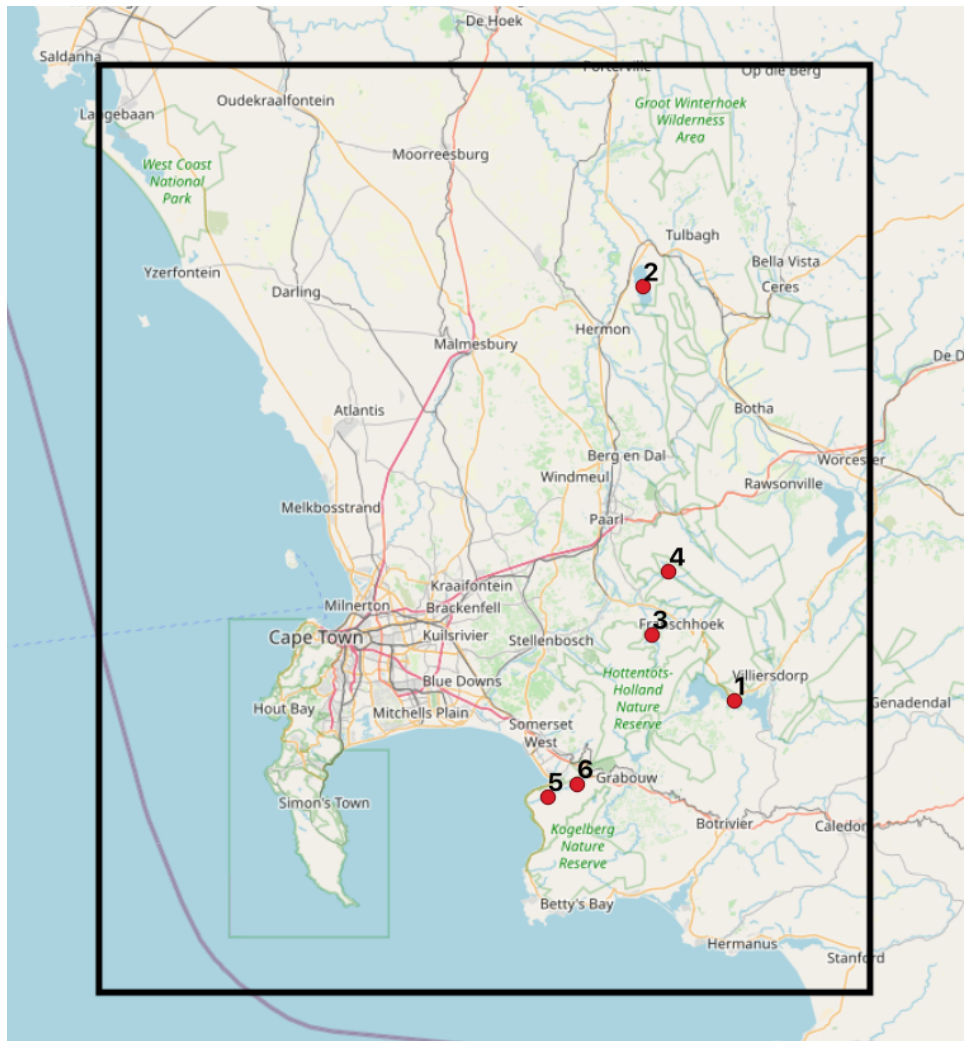


Figure 2. Spatial representation of the studied area. The frame shows the area of which precipitation data was collected, referred to as ‘Greater Cape Town Area’. The red dots show the location of the six largest dams in ascending order of volume: 1=Theewaterskloof, 2=Voelvlei, 3=Berg River, 4=Wemmershoek, 5=Steenbras Lower, 6=Steenbras Upper.

Next to a profile of the dam levels a profile of monthly precipitation in the Cape Town area has been made to gain a better understanding of the precipitation patterns of the last decades. For this analysis there is a distinction between precipitation from Cape Town and from Cape Town, including a greater area, from now on referred to as Cape Town Greater Area. This greater area is included since the six largest dams, providing almost all of the freshwater, are located outside Cape Town itself. The Cape Town Greater Area and spatial locations of the six largest dams can be seen in Figure 2.

The original precipitation data from NASA is the average precipitation for a grid of 0.5x0.5 degrees, the Greater Cape Town Area is a square of 3x3 of these grids. The average precipitation of these 9 grids has been combined to compute a working average which can be used for analysis. In order to test for trends in the precipitation data a Seasonal Mann-Kendall test has been conducted. This test is a non-parametric test that tests for monotonic trends in seasonal data. For this test the whole dataset of precipitation data was used, resulting in 38 years of usable data. The tested time period is from 1981 until 2019. The significance level for this test was set at 5%, so if the probability value was less than 0.05 the trend was evaluated to be significant. The Null-Hypothesis for this test is: *There is no trend*

in the series. The Seasonal Mann-Kendall test will produce two tables, one depicting the whole dataset, the other depicting the individual months. In the test all months are compared to the same month over the years, so all Januarys will be compared over the years to spot for an increase or decrease in precipitation for this month.

For the comparison between precipitation and dam levels only a small portion of the precipitation data has been used, since the dam levels are only available from 2012 onwards. A graph will show the combined data on precipitation and dam levels to show the relation between these variables. This analysis will answer the 1st sub question.

For further analysis the four RCP climate scenarios from the IPCC will be used. Each scenario will have a different expected influence on the global average temperature increase. For each scenario the impact on precipitation for South Africa will be predicted as precisely as data allows. The IPCC has made a prediction about precipitation change based on the average global increase of one degree Celsius (IPCC, 2015). This prediction is used to create a formula that combines the prediction of future temperature increase and the prediction of precipitation change per temperature increase. By using the computed current average annual precipitation, the future precipitation can be predicted.

Projected Precipitation = Current Precipitation · (Difference of precipitation · Increase of global average temperature)/100 + 1) or:

$$P = C \cdot ((D \cdot W)/100 + 1)$$

P = Expected Average Annual Precipitation

C = Current Average Annual Precipitation

D = Percentage difference of precipitation

W = Increase in global average temperature change in degrees Celsius

This formula is designed to calculate future annual precipitation based on the current annual precipitation and climate change variables impacting the precipitation. In this formula C will be calculated in the first section of the analysis by analyzing and computing the average annual precipitation based on historic precipitation data. Variable D is spatially dependent on the projection of the IPCC, in the case of the Cape Town Greater Area D ranges from -3 to -9. This value is derived from the IPCC (2017) as shown in figure 9. Variable W is dependent on the actual increase of global temperature in degrees Celsius, since the actual increase of temperature is uncertain the RCP's from the IPCC (2015) will be used to make predictions about this variable. This will result in an overview of the impact of the four RCP climate scenarios on precipitation for the Cape Town area. With the outcomes of these scenarios the freshwater availability of Cape Town in the future can be predicted. Additional information from the Cape Town local government on new projects to increase the freshwater supply in the future combined with the outcomes of the climate scenarios will answer the third sub question.

All of the analysis and sub questions combined will give an overview and prediction of the impact of the climate change scenarios on the precipitation in the Cape Town area, resulting in the future freshwater availability of the city. The analysis and findings combined will answer the main research question.

4 Results

4.1 Dam levels

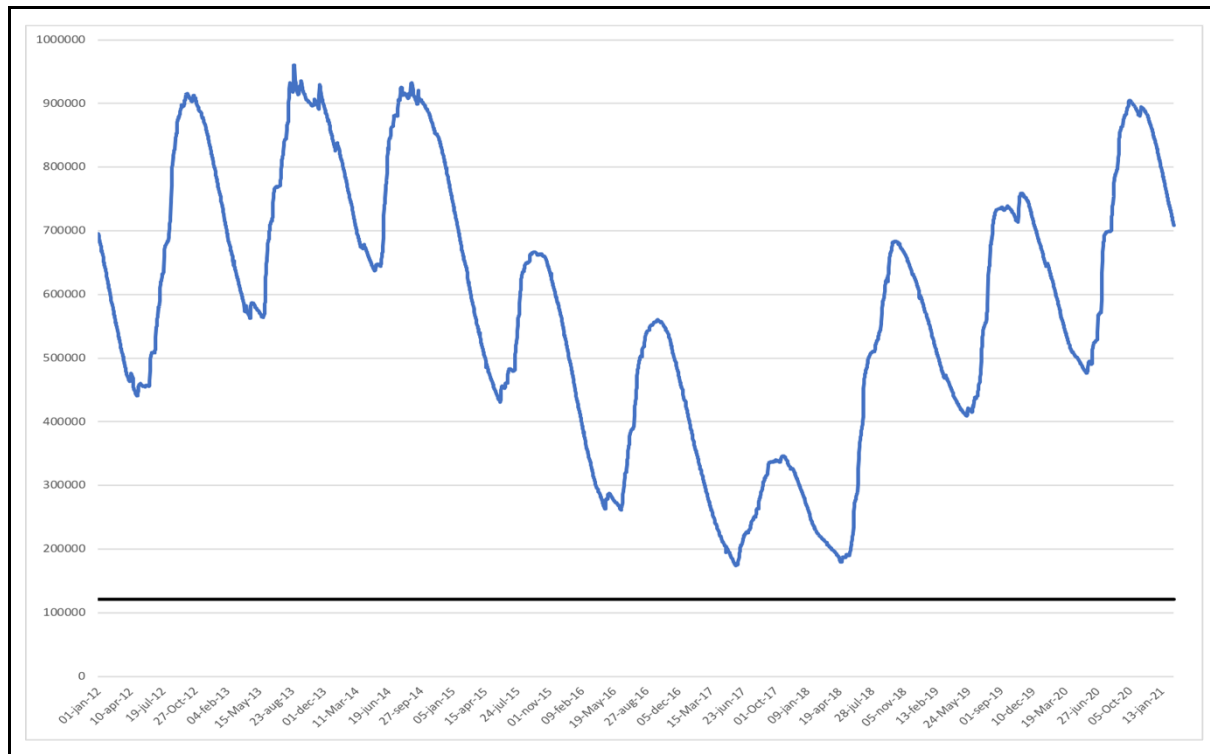


Figure 3. Combined water stored in the 6 major dams from 2012-2021.

In figure 3 the combined water storage in the 6 largest dam reservoirs is presented over the time period 2012 until the start of 2021. These 6 dams have a combined storage capacity of 898221 ML, adding up to 99.5% of the total water storage for Cape Town. The 8 smaller dams together have a storage capacity of 4304 ML, or 0.5%, and are therefore not included in the analysis. Important notion in figure 3 is the dependency of the winter rainfalls to restore enough capacity for the upcoming dry season. Another important notion is the sharp decrease of combined dam levels in the 2015-2018 period. The bar shows the 13.5% storage capacity threshold which would trigger the 'Day Zero' scenario.

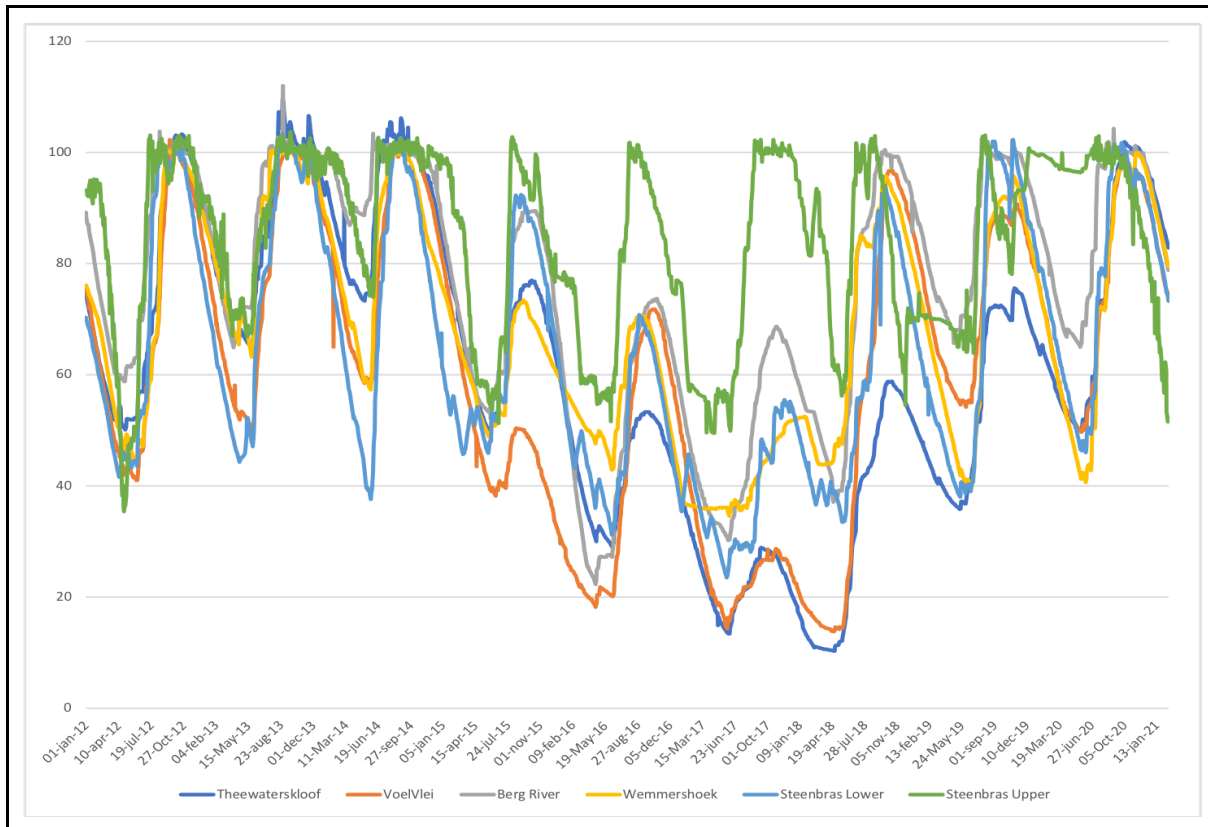


Figure 4. Relative dam levels from the six largest dams in Cape Town area from 2012 to 2021

The graph in figure 4 shows the percentage of storage capacity used for the 6 largest dams. Important notion here is that all dams are affected by the drought except for Steenbras Upper. Steenbras Upper does not only function as a freshwater reservoir, it also produces electricity through a system of pumps. Therefore, the water levels of Steenbras Upper are maintained artificially at a high level in order to guarantee enough water for electricity production. The two largest dams (Theewaterskloof and Voelvlei) are affected the most by the lack of precipitation in the 2016-2018 winter periods as the water levels drop to 10.3% and 13.8% respectively in April 2018. Other dams (Berg River, Wemmershoek, Steenbras Lower) did also not recharge to full capacity during the winter rainfalls in the 2015-2018, however the storage levels are not as low as Theewaterskloof and Voelvlei.

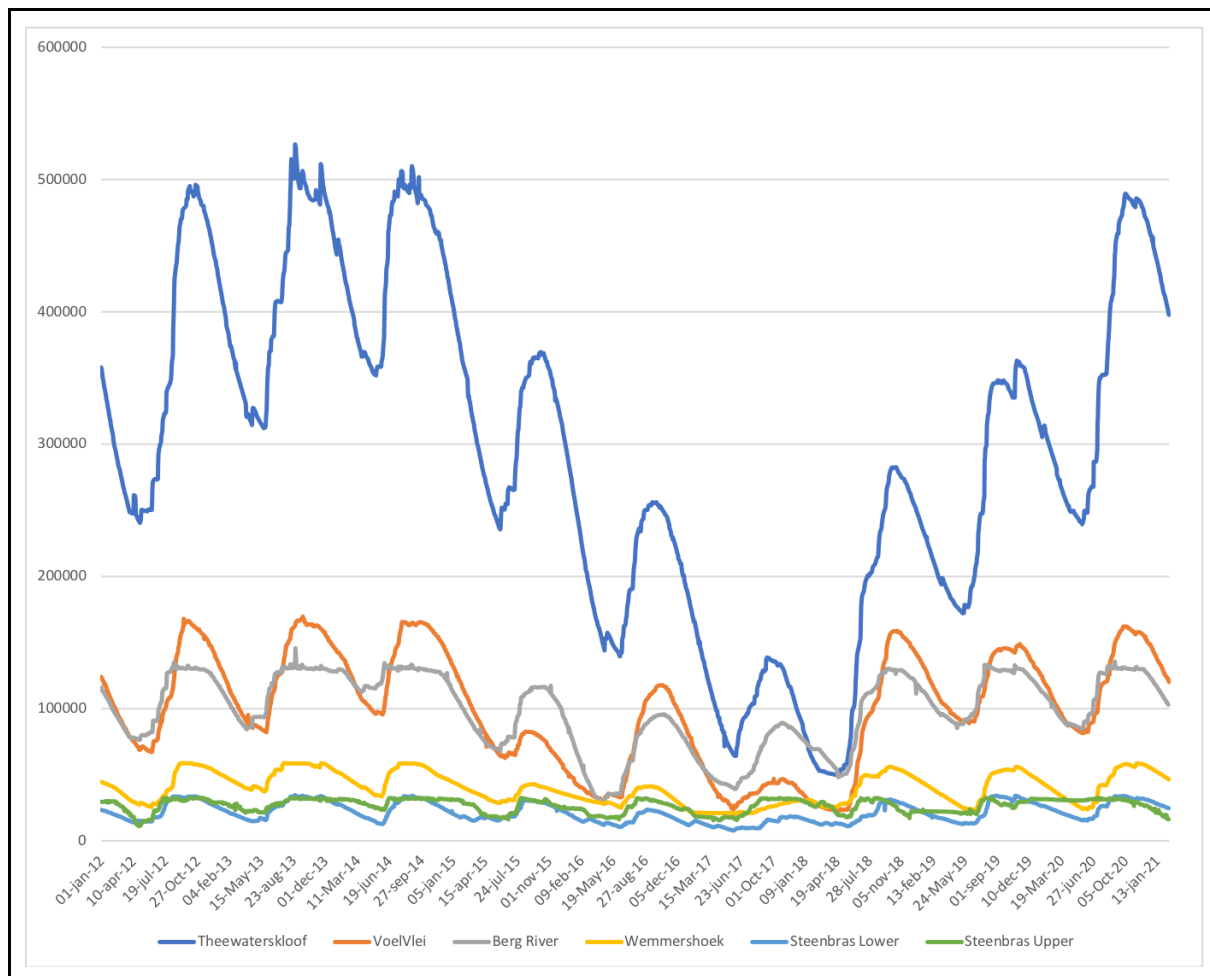


Figure 5. Dam levels in absolute numbers, from 2012-2021

Figure 5 shows the actual dam levels of the six main dams. It also shows the comparable storage capacities of the various dams. Clearly visible is that Theewaterskloof has the largest capacity by far, followed by Voelvlei and Berg River. The other three dams are considerably smaller in their capacity.

4.2 Precipitation

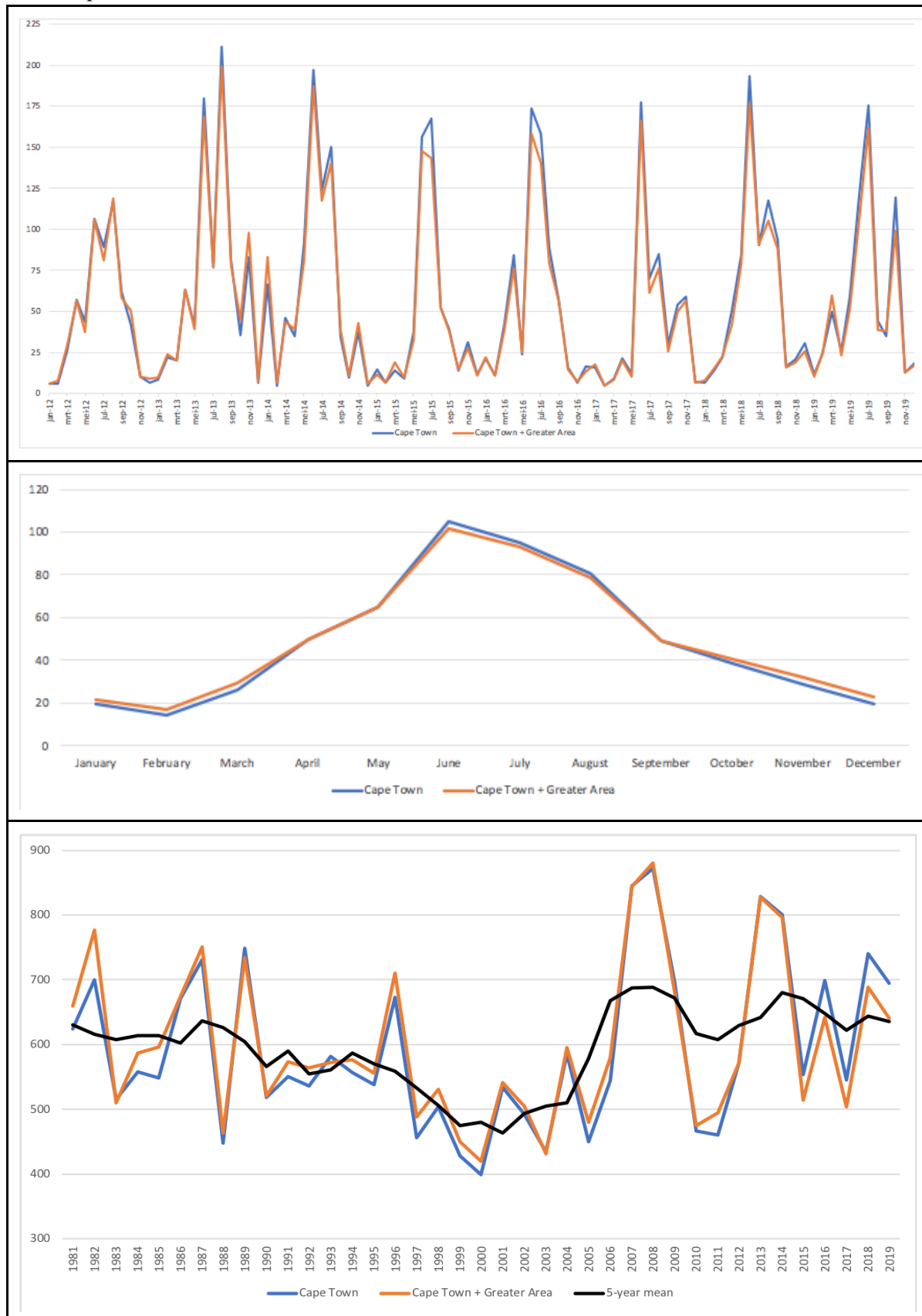


Figure 6a. Precipitation from 2012-2019 in Cape Town and Greater Area.

Figure 6b. Average monthly precipitation from 1981-2019 in Cape Town and Greater area.

Figure 6c. Annual precipitation from 1981-2019 in Cape Town and Greater area.

Figure 6a shows the precipitation in Cape Town and Cape Town Greater Area in the time period 2012-2019. Both areas are displayed to show the similarities, although the greater area is more mountainous and is further inland compared to the Cape Town area the precipitation patterns are fairly similar. This contradicts the City of Cape Town (2018) which states that precipitation is significantly higher in the mountainous areas around the dams. Figure 6b shows the dispersion of rainfall over the year, this clearly shows a peak of precipitation in the winter months compared to summer months, which confirms the statement of Natalie et al. (2019). Figure 6c shows the annual precipitation in both areas over the time period of 1981-2019. Based on this graph there is no monotonic trend over the whole time period. However, a decreasing trend in the 5-year mean can be seen from 1981 until 2001. Whereas after that the average mean goes up and then goes up and down, largely due to the large differences in annual precipitation in this period. Based on these graphs it can be seen that there is variability in the total annual precipitation, while the precipitation follows a pattern year-round.

Kendall's tau	-0,111
S'	-4,000
Var(S')	44,000
p-value (Two-tailed)	0,651
alpha	0,050

Figure 7a. Test results of the Seasonal Mann-Kendall trend test, model results.

Series\Test	Kendall's tau	p-value	Sen's slope
JAN	-0,031	0,790	-0,049
FEB	-0,112	0,321	-0,111
MAR	-0,203	0,071	-0,407
APR	-0,128	0,255	-0,516
MAY	0,001	1,000	0,003
JUN	0,266	0,018	2,033
JUL	0,088	0,439	0,632
AUG	0,266	0,018	1,428
SEP	0,001	1,000	0,005
OCT	0,001	1,000	0,002
NOV	0,247	0,028	0,593
DEC	-0,155	0,168	-0,257

Figure 7b. Test results of the Seasonal Mann-Kendall trend test, monthly results.

Figure 7a and b show the results from the seasonal Mann-Kendall trend test conducted on the precipitation data from the Greater Cape Town region from 1981-2019. Figure 7a shows that the model itself is not significant, this means that we cannot reject the null-hypothesis: *There is no trend in the series*. This means that there is no significant increasing or decreasing trend in the precipitation data. This supports our findings of Figure 6(c) that there is no monotonic trend in the annual precipitation. Although in figure 6c two periods can be distinguished in the 5-year mean, 1981 until 2004 shows a decreasing trend in the 5-year mean, while from 2004 the average increases again. However, the variability between the various years seems also to be larger than in the 1981-2004 period. The seasonal Mann-Kendall trend test tests only for upward or downward trends in the dataset, when there are multiple trends in the same dataset the model will not be significant. However, the test provides us also with results of the individual months shown in Figure 7b. It should be noted that 3 months are significant. These months are June, August and November. For these months Kendall's tau and Sen's slope are both positive, indicating that there is a positive precipitation trend in these

months. This means that the precipitation in these months is increasing over the years. This contradicts our expectation of a decrease in precipitation over the years. However, since the model itself is not significant nothing can be said about trends in the entire dataset, and consequently a decrease in annual precipitation cannot be excluded. With a p-value of 0.071 March March is close to being significant with a confidence level of 0.05. It seems that there is a trend in probability values with a month being (almost) significant every 2 or 3 months. The main difference between March and the three significant months is the Sen's slope. For March Sen's slope is negative, indicating that there is a decreasing trend in precipitation in March over the time period.

4.3 Combined analysis Precipitation / Dam Levels

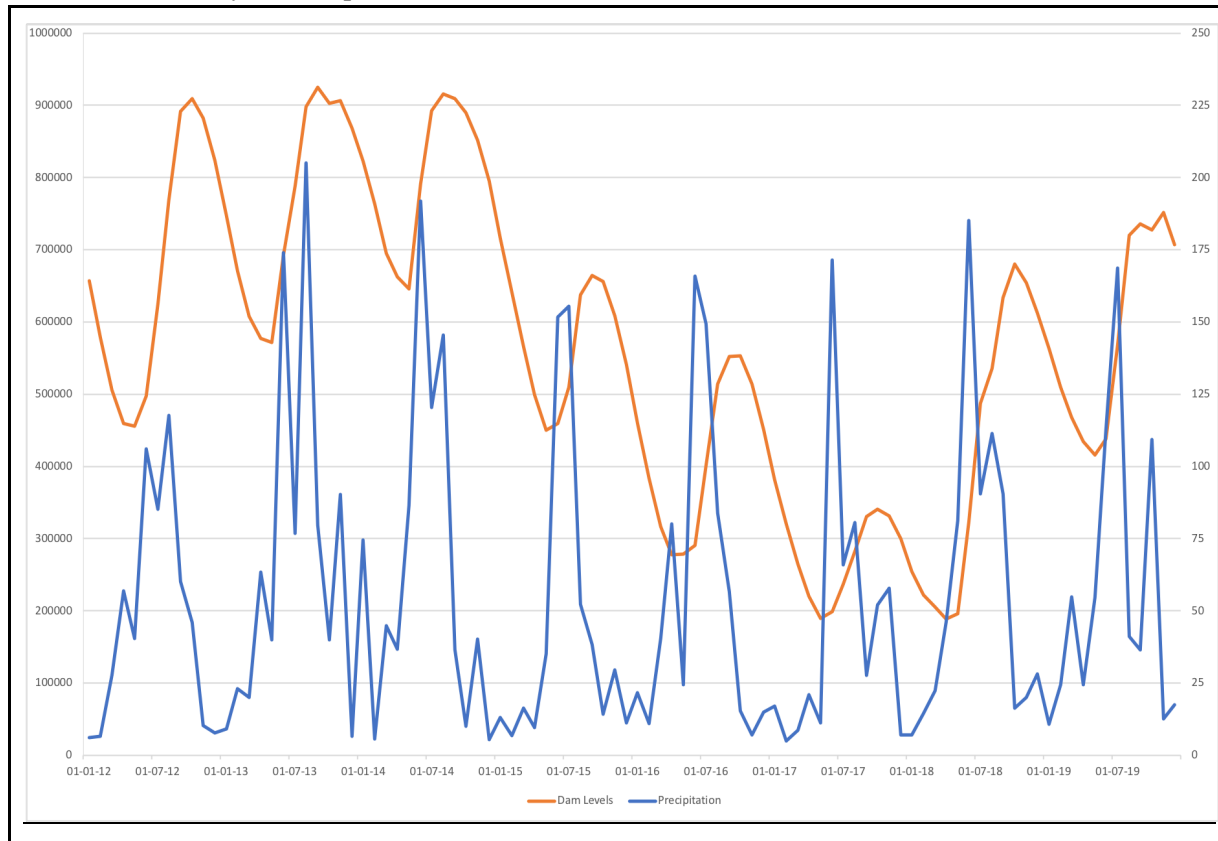


Figure 8. Historic precipitation and dam levels from 2012 until 2019 on a monthly basis.

Figure 8 shows a combination of the 6 largest dam levels and the precipitation from 2012 until 2019. Notions here are the correlation between the upward dam level during peaks in precipitation, and a decrease in dam levels in dry periods. The period of low dam levels in 2015-2018 is clearly visible, however at first glance the precipitation in that same period of time does not look that problematic. However, as seen in Figure 6c annual precipitation in the 2015-2018 period is lower than the 2012-2014 period, supporting the findings of Otto et al. (2018) that a lack of precipitation was a key variable for the water crisis. An explanation for this can be found in the sharp single peaks in precipitation from 2015-2018, indicating that the rain season is shorter than the broader peak of previous years.

4.4 Climate Change impact

In order to establish the impact of climate change on future annual precipitation a formula has been created based on current precipitation, RCP scenarios from the IPCC (2015) and precipitation projections from the IPCC (2017). The formula has been discussed in the Methodology section of this thesis.

$$P = C \cdot ((D \cdot W)/100 + 1)$$

To establish future expected average annual precipitation (P), the current average annual precipitation (C), percentage difference of precipitation (D) and increase in global average temperature change (W) need to be established.

The C can be derived from the precipitation analysis. The average annual precipitation over 20 years (1986-2005) for Cape Town is 542mm, the average for the greater area including Cape Town is 556,9 mm. For this analysis the average of the Greater Cape Town area will be used, since this includes the spatial area where all dams are included. The specific time period is chosen to match the corresponding time period of which D can be derived.

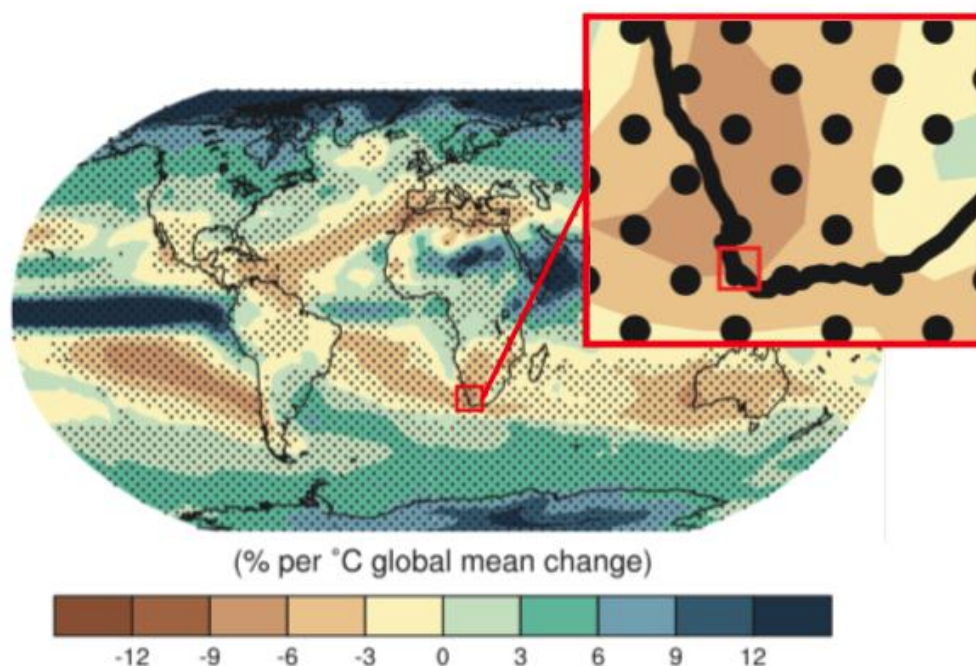


Figure 9. Precipitation change in 2081-2100, % per °C compared to 1986-2005 time period (derived from IPCC, 2017, Page 1061, Figure 12.10, modified)

The D can be derived from Figure 9. This figure displays a categorical representation of Earth, where precipitation change is displayed per degree Celsius increase of the global mean. The percentual change is compared to precipitation data from 1986-2005, therefore the current average annual precipitation (C) has been calculated over the same time period. Zooming in on South Africa learns that Cape Town is categorized in the category -9/-6, while a small portion of the studied Greater Cape Town area falls in the -6/-3 category. For this analysis an interval from 1.5 between -3 and -9 will be used, this will allow for detailed analysis and include the uncertainty range of the model into the analysis.

	2081-2100	
RCP	Mean	Likely range
2.6	1.0°C	0.3°C to 1.7°C
4.6	1.8°C	1.1°C to 2.6°C
6.0	2.2°C	1.4°C to 3.1°C
8.5	3.7°C	2.6°C to 4.8°C

Figure 10: RCP Pathways from the IPCC (2015). Global Mean Surface Temperature Change for each of the RCP Scenarios.

The W can be derived from the RCP projections of the IPCC. The four RCP scenarios all represent a pattern of different greenhouse emissions resulting in various ranges of mean surface temperature increase. Using the RCP temperature projections as a variable in the formula allows for projections made for each range. For each RCP the low, mean and high range will be used as input for the formula, this ensures that the range is also represented in the analysis. These variables are shown in Figure 11.

RCP 2.6			RCP 4.6			RCP 6.0			RCP 8.5		
Low	Mean	High	Low	Mean	High	Low	Mean	High	Low	Mean	High
0.3°C	1.0°C	1.7°C	1.1°C	1.8°C	2.6°C	1.4°C	2.2°C	3.1°C	2.6°C	3.7°C	4.8°C

Figure 11: Temperature ranges for each RCP, used as variables in the formula. Derived from the IPCC (2015).

Now that all of the variables are known, this will result in the following inputs:

$$P = C \cdot ((D \cdot W)/100 + I)$$

P = Variable that will be calculated, in average mm per year.

C = 556,9 (mm)

D = Interval of 1.5 between -3 and -9.

W = All values of Figure X. Being the low, mean and high values of each RCP projection.

	RCP 2.6			RCP 4.6			RCP 6.0			RCP 8.5		
	Low	Mean	High	Low	Mean	High	Low	Mean	High	Low	Mean	High
-3.00	551.89	540.19	528.50	538.52	526.83	513.46	533.51	520.14	505.11	513.46	495.08	476.71
-4.50	549.38	531.84	514.30	529.33	511.79	491.74	521.82	501.77	479.21	491.74	464.18	436.61
-6.00	546.88	523.49	500.10	520.14	496.75	470.02	510.12	483.39	453.32	470.02	433.27	396.51
-7.50	544.37	515.13	485.90	510.96	481.72	448.30	498.43	465.01	427.42	448.30	402.36	356.42
-9.00	541.86	506.78	471.69	501.77	466.68	426.59	486.73	446.63	401.52	426.59	371.45	316.32

Figure 12. Results of all variables in the formula. Expected average annual precipitation in 2081-2100 per RCP scenario and % interval.

	RCP 2.6			RCP 4.6			RCP 6.0			RCP 8.5		
	Low	Mean	High	Low	Mean	High	Low	Mean	High	Low	Mean	High
-3.00	-0.90%	-3.00%	-5.10%	-3.30%	-5.40%	-7.80%	-4.20%	-6.60%	-9.30%	-7.80%	-11.10%	-14.40%
-4.50	-1.35%	-4.50%	-7.65%	-4.95%	-8.10%	-11.70%	-6.30%	-9.90%	-13.95%	-11.70%	-16.65%	-21.60%
-6.00	-1.80%	-6.00%	-10.20%	-6.60%	-10.80%	-15.60%	-8.40%	-13.20%	-18.60%	-15.60%	-22.20%	-28.80%
-7.50	-2.25%	-7.50%	-12.75%	-8.25%	-13.50%	-19.50%	-10.50%	-16.50%	-23.25%	-19.50%	-27.75%	-36.00%
-9.00	-2.70%	-9.00%	-15.30%	-9.90%	-16.20%	-23.40%	-12.60%	-19.80%	-27.90%	-23.40%	-33.30%	-43.20%

Figure 13. Results of all variables in the formula. Expected average annual precipitation in 2081-2100 per RCP scenario and % interval. In % decreased from the average annual precipitation from 1986-2005.

Figure 12 and 13 show the results of all variable combinations in the formula. They show that all scenarios predict a decrease in annual precipitation rates, since all predictions are lower than the original annual average of 556,9mm. It also shows that the range of predicted annual precipitation is quite extensive ranging from 551.89mm in the RCP 2.6 Low scenario with a variable of -3.00, to 316.32mm in the RCP 8.5 scenario with a variable of -9.00. A decrease in annual precipitation was to be expected due to the D variable which is negative for all scenarios (-3 till -9), there is an expected decrease in precipitation for every degree Celsius increase of the global average mean. This supports the findings of the IPCC (2017) that a precipitation decrease is very likely (>90% of the simulations) in winter months (JJA) and likely (>66% of the simulations) in summer months (DJF). Figure 11 includes the widest ranges of the D variable and RCP estimates, a combination of the widest ranges therefore results in the most extreme results of expected precipitation. Although the widest range is included, it should be remembered that for both variables the actual numbers are most likely more moderate. The D variable is retrieved from a map projection (Figure 8), showing a relatively small area Northwards from Cape Town being categorized as -9 / -6, while most of the surrounding area is in the -6 / -3 category. The studied area did mostly fall into the -9 / -6 category but was partially on the border of the two categories, indicating that the actual numbers are likely to be on the low end of the category. Regarding the RCP scenarios, the RCP 8.5 is the high-end scenario where little is being done to stop emitting greenhouse gasses. Although not impossible, efforts are being made around the globe to reduce emissions and avert the RCP 8.5 scenario. On the other end, the RCP 2.6 is a very positive scenario with emissions being cut drastically on short notice, therefore it does not seem like this scenario will become reality.

4.5 Combined analysis Climate Change / Precipitation

As can be seen in Figure 12 and 13 there will be a predicted decrease in precipitation under all scenarios. To translate the decrease in precipitation to a prediction of future dam levels the percentages of Figure 13 are used to indicate future dam levels.

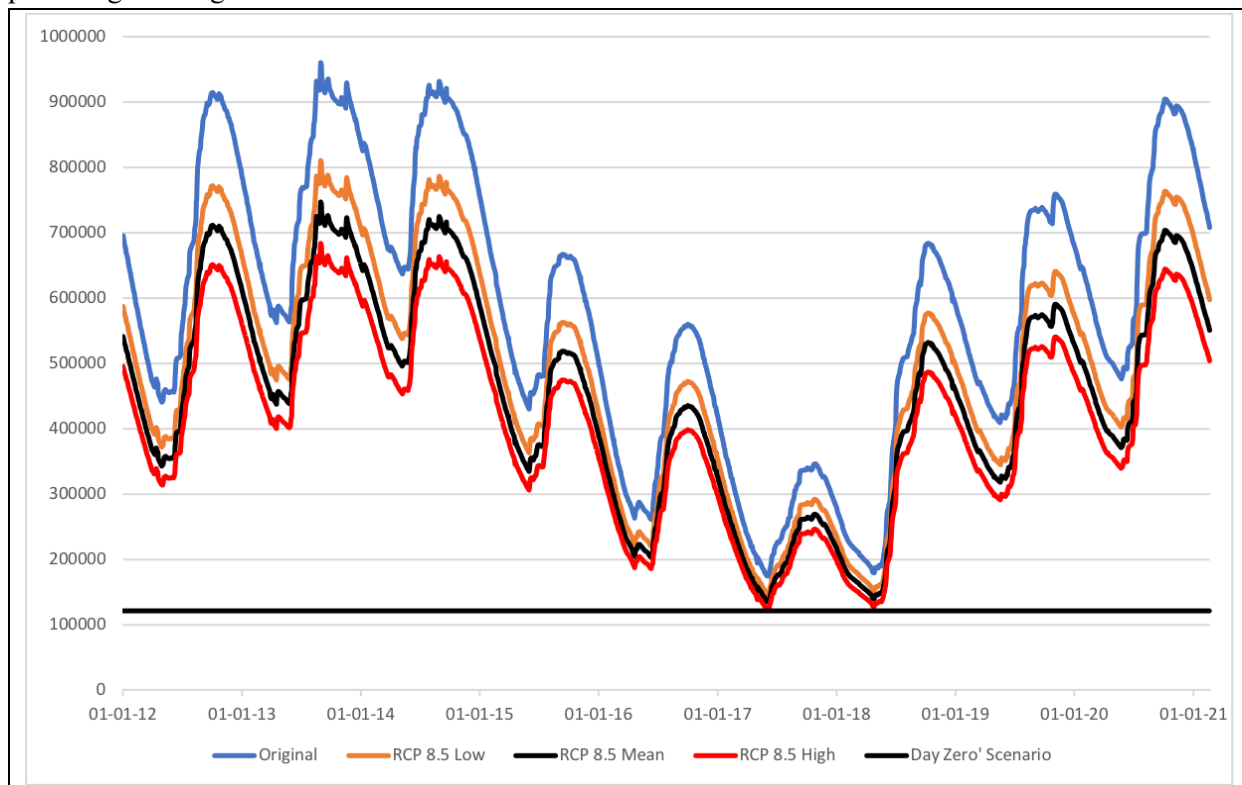


Figure 14. Dam levels under the RCP 8.5 scenario.

In Figure 14 the historic dam levels of 2012 until the beginning of 2021 have been decreased with the RCP 8.5 results of figure 12, the mean value for the D variable of -6.00 has been used. This results in a decrease of 15.6% under the RCP 8.5 Low scenario, 22.2% under the RCP 8.5 Mean scenario and 28.8% under the RCP 8.5 High scenario. This graph is however not representative for the actual influence of the decreased precipitation on the dam levels, but only shows the percentage decrease of dam levels. A representative graph would need data on water consumption and evapotranspiration over the same period as input as well, in order to calculate the in and outgoing water flows. Although not accurate figure 14 gives an insight on permanent decreased storage levels and its implications. In this model the storage levels approached the 'Day Zero' scenario at 13.5% capacity in two summer periods in a row. The lowest dam levels in this model were 13.77 and 14.21 respectively, marginally above the 13.50 percent threshold.

4.6 Societal impact

The aforementioned results are a prediction of Cape Town's future freshwater supply from the existing dam infrastructure, which is responsible for 96% of the total freshwater supply. Only 4% is currently coming from other sources, this number is scheduled to be 25% in 2040 as Cape Town is diversifying its water sources (City of Cape Town, 2020). This diversification is needed to decrease the dependency on precipitation as the main freshwater source. Other sources considered include seawater desalination; water reclamation; ground water extraction; diversion of Lourens, Upper Wit and Molenaars rivers and removing alien vegetation in key-areas (City of Cape Town, 2018).

The diversification and expansions of water sources are needed in order to keep up with the water demand of a thirsty and growing city. Cape Town has a large tourist sector responsible for 10% of the economic output (Parks et al., 2019), this sector is vulnerable to water shortages; incoming tourists declined 20% during the peak water shortage of 2018 (Hyman, 2019). Also, agricultural output decreased by 400 million USD (OECD, 2021) indicating that the water shortages had large financial consequences for Cape Town.

The growing population also increases the need for expanding existing water infrastructure. The population of Cape Town has been growing at over 2% per year since the 1950's. Although the growth rate is expected to decrease to around 1.5% annually in 2030, another 1 million inhabitants will be added to the city's population in 2033 (United Nations, 2019). Furthermore, the social inequality in Cape Town needs to be addressed, as already many Capetonians lack access to freshwater (Ziervogel, 2018; Parks et al., 2019). Fear is that as water is becoming scarcer the inequality will only grow bigger (Millington & Sheba, 2021).

5 Concluding paragraph

5.1 Conclusion

A quantitative data analysis has been used to answer the main research question "*What impact does change in precipitation patterns have on the future freshwater availability of Cape Town, South Africa?*". Various types of data were analyzed independent and dependent from each other. The combined precipitation and dam level analysis showed a correlation between these two variables, indicating that precipitation has a direct influence on the volume of the dam reservoirs. This analysis answered the first sub question.

A prediction of future annual precipitation was made by a combination of historic precipitation data, IPCC precipitation projections and the IPCC's RCP scenarios. The outcome of the created formula resulted in a table with future annual precipitation rates under various combinations of the precipitation projections and RCP scenarios. The main finding was that the precipitation is going to decrease under each scenario and is largely influenced by the average mean temperature and variability in precipitation projections. These findings support the claims by Trenberth (2011), Dosio et al. (2019) and the IPCC (2015, 2017). This analysis answered the second sub question.

Consequently, the projected precipitation was translated to future dam levels to indicate future water supply from the existing infrastructure. This analysis was flawed due missing data on water consumption and evapotranspiration, which were needed in order to create an accurate prediction of in and outgoing water flows. However, the graph gives an indication on decreased water levels under the RCP 8.5 scenario.

All in all, we can conclude that Climate Change will have a negative influence on the precipitation for Cape Town and surrounding areas and will therefore impact the freshwater availability for the city. However, it remains unclear to what extent the average precipitation will decrease. It should be remembered that climate change does not only affect precipitation patterns, but also increases the chances of irregular events and extreme droughts. Combined with a growing population it is clear that Cape Town needs to diversify its water supply in order to prevent a new 'Day Zero scenario' in the future.

5.2 Research recommendations

The research mainly focused on the influence of climate change on precipitation and its result to future freshwater availability. However, there are more factors such as evapotranspiration, vegetation, population change and water use that influence the total water supply and demand. In order to fully understand and predict the availability of freshwater in the future all of these factors need to be considered. Since these factors are highly connected a combined study on all variables need to be conducted in order to make accurate predictions about the future fresh water supply and demand.

5.3 Limitations

The research is partially limited by data availability. The secondary data has been collected from various sources, all maintaining various intervals and available year records. This especially affected the analysis on the historic dam levels since data was only available from 2012 onwards, therefore the correlation analysis with precipitation was not as extensive. Another data limitation was the precipitation data, various datasets with daily intervals where not accessible. Therefore, another dataset with monthly intervals had to be used, diminishing the accuracy of the analysis. The data was not available Since daily precipitation was not available, the accuracy of the prediction of future dam levels/freshwater availability could not be analyzed according to the original intended method.

Another limitation in researching climate data is the uncertainty when it comes to projections for future patterns. Since climate change is highly uncertain and its trajectory is dependent on future human actions, all predictions include a high degree of uncertainty. All models used as input for the analysis are solid models from the IPCC; it has a solid basis, however building and combining these models decrease its accuracy and make accurate conclusions very difficult.

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