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Precipitation variations and shifts over time: Implication on Windhoek city water supply

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ABSTRACT

The scarcity of freshwater is a growing concern around the world, especially in the developing world and is increasingly threatening human survival in less affluent parts of the world. In arid and semiarid regions, freshwater resources are imperative for the survival of populations as well as development activities in urban centres. Preceding assessments for potential solutions have underestimated the scarcity of water by failing to capture main trends of precipitation and the extent of drought periods. This paper aims to investigate rainfall trends for the City of Windhoek, Namibia. A century scale is examined by reconstructing historical precipitation records, and future trends are subsequently estimated and interpolated using Ordinary Kriging in ArcGIS 10.3. Kriging responds and handles spatial correlation much better for observed data points. The results show locations that receive high rainfall and potential periods for harvesting rainwater. The findings further show that the periods of high rainfall are shorter, and after each high rainfall stretch, a long period of lower rainfall follows immediately. Each low rainfall period is anticipated to last longer than the previous one. These scenarios are highly significant for urban managers in dryland cities such as Windhoek, as they demonstrate when water would need to be extra sparingly managed. This study highlights the need for better water management strategies, if cities in dry climates are to survive the anticipated future water crises.

1. Introduction

Water shortage is one of the most serious emerging socio-economic and environmental problems world-wide, and is mostly felt in semi-arid and arid regions. This shortage is aggravated by the increase in water demand of the fast-growing populations worldwide (Falkenmark, 2016; Varis et al., 2006; Sharma et al., 2014). It is further amplified by the change in climate through reduced precipitation and changes in other climate variables such as in temperature (Dahm et al., 2002; Gober and Kirkwood, 2010; Schewe et al., 2014). Consequently, long drought periods have intensified the critical nature of water shortages, especially in Africa (Chartres and Williams, 2006; Schewe et al., 2014). Accordingly, the deficiency in water supply limits the potential of development activities, affecting the well-being of societies at large (Ohlsson and Turton, 1999; Showers, 2002; Gumbo, 2003; Wang et al., 2009). Nearly a quarter of the world's population will experience severe water scarcity within the first quarter of the next century and approximately a billion people in arid regions will face absolute water scarcity by 2025 (Seckler et al., 1999; Ruth et al., 2007). The domestic demand in urban areas is anticipated to rise by 50% between 2010 and 2030 (Lafforgue and Lenouvel, 2015).

In southern Africa, Namibia is by far the most arid country and is predominantly characterised by minimal amounts of rainfall, periodic droughts and high annual evaporation rates 2,100 mm/year (Mendelsohn et al., 2002; Kluge et al., 2008; Zimmermann et al., 2012). Some of the urban centres in Namibia (mostly in the north-eastern and central regions) suffer less harsh consequences of the hydrological cycle since they receive higher amounts of rainfall (Mapani, 2005; Sarma and Xu, 2017; Voarintsoa et al., 2017). The city of Windhoek has become plagued by persistent water shortages that induced a water crisis over the past years, especially 2016, and by May 2017, the severe drought in Cape Town, South Africa had been declared a national disaster; of such magnitude that none had never been experienced in an century (BBC World News, 13 Feb., 2018). A combination of rapid population growth and changes in rainfall patterns have exacerbated the water scarcity in the city of Windhoek (Lahnsteiner and Lempert, 2007; Onyango et al., 2014). With fierce competition for water consumption, the continuous water shortage in the city impacts severely on the development activities and water dependant industries (The Namibian Economist, 2015; Lafforgue, 2016). Traditional means of dams, surface reservoirs and

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boreholes appear to be insufficient (Lafforgue, 2016). Therefore, in adaptive management strategies, it important to consider precipitation trends and its impacts on water supply.

In response to several years of recurrent water crises and the efforts to manage water more sparingly, several investigations have been carried out in Windhoek water (Kavezeri-Karuaihe et al., 2005; Magnusson, 2005; Magnusson and van der Merwe, 2005; Lahnsteiner and Lempert, 2007; Flod and Landquist, 2010; Nashima et al., 2013). However, by the year 2015, Windhoek had a severe drought where reservoirs had only enough water for 12 months (City of Windhoek, 2015). City managers had to apply compulsory water saving measurements, targeting a reduction of water usage of at least 35% (City of Windhoek, 2015; The Namibian, 2015; New Era, 2016).

An earlier report by the Intergovernmental Panel on Climate Change (IPCC) emphasised the importance of studies that focus on detailed climate aspects in water stressed areas (IPCC, 2007), yet such a detailed analysis of precipitation trends is still lacking for Windhoek. Such understanding is fundamental for practical long-term planning. This paper aims to address this gap and investigate the rainfall trends of Windhoek. Specific objectives include: (1) to determine trends in rainfall over the past 100 years and make projected estimates for the next 40 years, and (2) to determine the most suitable periods for harvesting rain water.

2. Material and methodology

2.1. Study area description

Windhoek is the capital city of Namibia, and hence houses several important institutions of government and diplomatic missions. The city is the country's centre of economic activity, and accounts for more than 50% of the country's manufacturing activities, businesses and finance services (Mapani and Schreiber, 2008; Pendleton et al., 2014). The city lies in the central part of the country, which makes the accessibility easier for migrants and transportation, making it home to 15% of the 2.1 million national's total population (National Planning Commission, 2012; Pendleton et al., 2014), with a growth rate of 4.5% per annum (Frayne, 2007; Nashima et al., 2013; Pendleton et al., 2014).

Of all the Namibian urban centres, Windhoek has the highest percentage of the country's population, consequently the demand for water consumption is very high. The city total annual water consumption is reported to have been approximately of 21 million m^3, by the year 2004–2005, which translates into an average demand of over 50,000 m^3/day (Mapani, 2005; Lahnsteiner and Lempert, 2007). The city main water sources are the municipal dams (80%, i.e. von Bach and Avis dams), which collect water from the catchment surface water runoff while the second source (10%) is the recycled water from waste water at Goreangab water reclamation plant and the third source (10%) is water from 50 municipal boreholes (Mapani, 2005; Nashima et al., 2013). At times, the city endures dry spells that lasts for about 4 consecutive years and uses over 4 million m^3 potable water from the boreholes for water supply (Lahnsteiner and Lempert, 2007). Vegetation cover is naturally limited due to aridity and is predominantly Acacia savanna woodland and limited grass cover (Harper and Maritz, 1998; Gold et al., 2001; Mapani, 2005, see Fig. 1a). The topography around Windhoek urbanised area is shown in Fig. 1b. Windhoek area rises from the NW towards the SE, in general. This topography has a marked effect on the development of settlements. The contour map shows the variation of slopes throughout the urbanised area (Fig. 1c). The study focuses on the urbanised area, which is around 16 km^2.

The city's main rainfall period is in summer, particularly between October and April (Fig. 2). The dry period lasts from May to August, which is mainly the winter time. The annual average rainfall ranges between 300 and 350 mm while the average temperature ranges between 18 and 20 °C (Mendelsohn et al., 2002).

Regional studies have consistently shown that water scarcity will be more severe in the face of climate change coupled with issues of poor management and distribution (Srinivasan et al., 2012). McDonald et al. (2011) present a study of major urban centres across the globe with more than 2 million inhabitants. Their study shows that water crises can be managed, but the hydrological cycle forms the base from which to work. The study further shows that southern Africa, especially the Gauteng province will experience a severe water shortage by 2050 if measures are not put in place to match the current urban migration trends. Namibia especially the area around Windhoek is predicted to have moderate water crises by 2050 (McDonald et al., 2011). Groisman et al. (2005) studied precipitation trends on the continents of North America, Russia, Australia and parts of South America (Brazil) and Africa (South Africa). They found out that the output from Global Climate Models (GCMs) is usually at variance with observational data due to issues of scale. The study further found that precipitation patterns in the study areas will tend to have extreme values, however the distribution patterns will likely change in all these regions (Groisman et al., 2005). The study also pointed out that the aridity for South Africa will increase with time towards the north-western part of the country, which is towards Namibia.

2.2. Methodology

To determine trends in rainfall for the city of Windhoek, monthly rainfall data spanning the period between 1891 and 2016 was obtained from the Windhoek official meteorological station. Additional monthly data was obtained from three private stations for the period between 1945 and 2016. The use of such long-term records is often used to explore trends and variabilities for climate conditions (New et al., 2001).

Determining of trends for precipitation is based on a time series of long term data sets (over a 100 years) as per availability of the data. An IBM SPSS version 21 and Microsoft Excel 2013 were used to clean the data to allow reliable results and interpretations. Ten (10) years per moving average method was applied to smoothen out seasonal rate fluctuations from monthly rainfall data, improving the impression of the patterns as the data showed no overall trend.

Precipitation values are available from four-gauge stations, based on point observations for future estimation and for the spatial interpolation. The gauges stations are separated by a distance of no more than 5 km. For instance, the Windhoek Waterwerke and Convent are 3 km apart whereas the Convent gauge station and Weernkatoor are around 5 km apart, finally the Weernkatoor and Klein Windhoek Mission station are only 2 km apart.

Using the forward modelling Kriging software in ArcGIS, we used the 100 years smother data to estimate for the next 44 years. Then this was compared by forwarding modelling from the 1945 data to 2060 and returned a similar result. Although the annual total rainfall data were calculated from 1891 to 2016, the estimates could only be based on the data starting from 1945 because not all private stations had records data going back to 1891.

With the spatial interpolation, precipitation data from observations are used to estimate spatial data for the entire surface for only the urbanised area (16 km^2) of Windhoek using ArcGIS 10.3. Two main groups of methods are available for spatial interpolation, the deterministic (Inverse Distance Weighted and Spline) and geo-statistical (Kriging) method (Kumar and Santosh, 2015; Ozturk and Kilic, 2016). The study used the Ordinary Kriging method for spatial interpolation with the guidance of Schmidt et al. (2011). Unlike deterministic methods, the Kriging tool has an advantage of yielding better results of unbiased predictions, with the least variance while also taking into account spatial correlation between the observed data points (Waller and Gotway, 2004; Moral, 2010; Schmidt et al., 2011; Ozturk and Kilic, 2016). Kriging also responds and handles kriging weights much better for spatial data (Schmidt et al., 2011; Ozturk and Kilic, 2016).

Rainfall distribution of an area with a mountainous terrain can vary significantly due to topographic factors (such as elevation, slopes of the

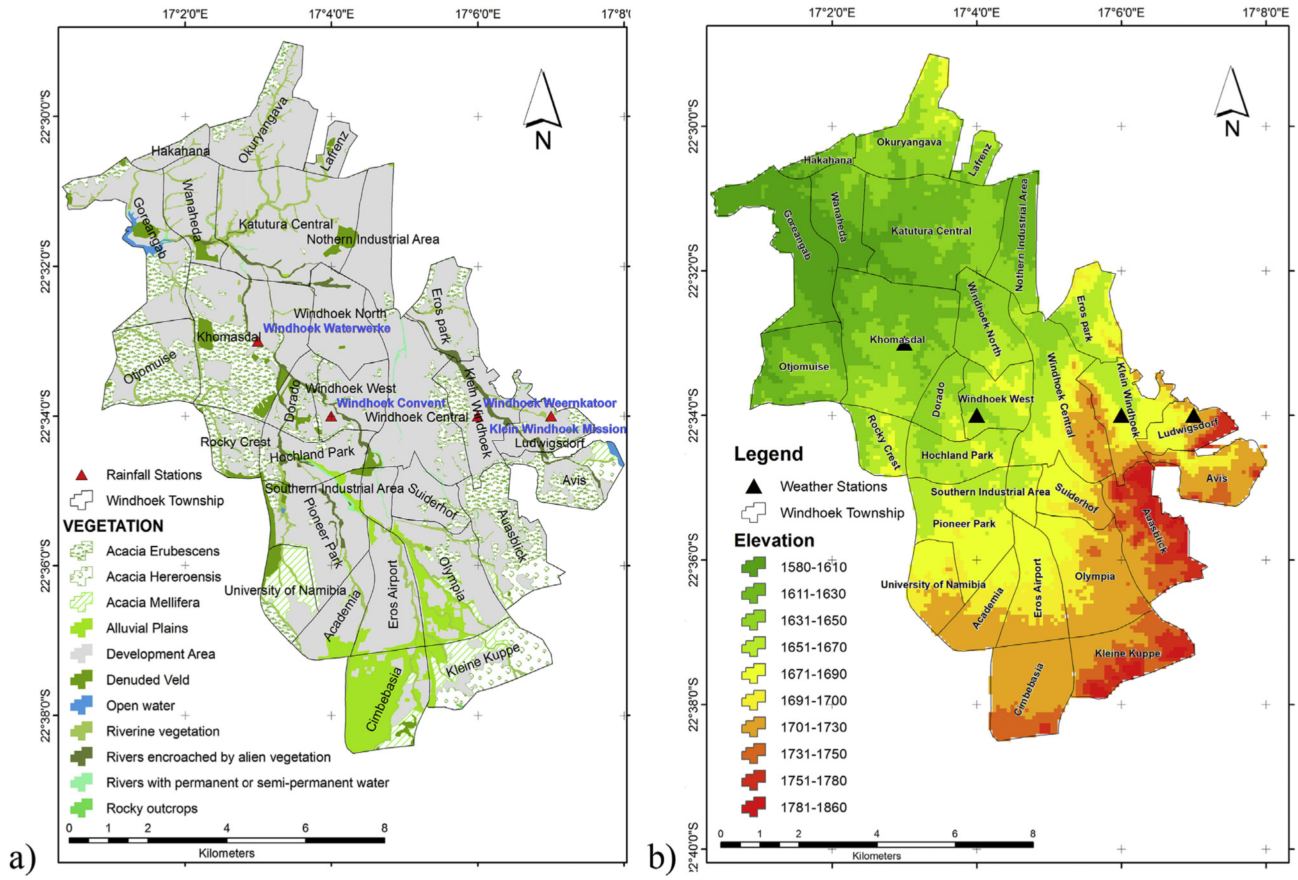


Fig. 1. Map of the city of Windhoek urbanised area, (a) vegetation cover (adapted from Shikangalah, 2017), (b) Elevation and (c) contour (Mendelsohn et al., 2002).

mountain etc) and climatic factors (such as rainfall, temperatures, wind directions, and speed, etc). The elevation is the most important influencing factor due to the orographic effect on mountain terrain (Taher and Alshaikh, 1998; Goovaerts, 2000; Buytaert et al., 2006). To cater for the topographical effects, the study extracted elevation values (Fig. 1b) at each gauged station derived from the DEM (30 m resolution) and incorporated the values in the GIS database by joining the shape files to the ones of rainfall after Kumar and Santosh (2015).

The approach was compared with the work of Mann (1945); Helsel and Hirsch (2002) and that of Kendall (1975). Mann (1945) first suggested using the test for significance of Kendall's tau where X-variable is time, a test for trends, exactly the approach we have used. This was directly cognate to regression, and thus the Mann-Kendall test can be simply stated as an approach to test for trends in one variable (Y = rainfall) against time (X). It must however be understood from the start that water resources data generally shows departures from the Gaussian distribution (Helsel and Hirsch, 2002), as such other tests that can be applied must be used as well. Based on the available monthly data between 1891 and 2011, a Standardised Precipitation Index (SPI) on 12 months period was used to identify the wet and drought periods (Hayes et al., 1999; Rouault and Richard, 2005; Li et al., 2008; Viste et al., 2013).

3. Results

3.1. Trends in annual and monthly local rainfall

Fig. 3 shows total annual rainfall for the city of Windhoek. Even though the Mann- Kendall trend test shows no outstanding monotonic trend (tau = 0.026, p value = 0.67) in the rainfall pattern, a generalised linear regression indicated quite a recovery from a drought between 1996 and 2011 (Fig. 3a). The most outstanding aspect of the yearly rainfall series is the immediate occurrence of the very low rainfall period (less than 250 mm) after each high rainfall (mostly higher than 500 mm) year (Fig. 3a). In the same trend, the city periodically (seven times from 1891 to 2011) received annual rainfall above of 700 mm, with an exception of the year of 2011 when the highest rainfall of around 1000 mm per annum was received. During 2011, January alone received over 320 mm of rainfall (Fig. 4), followed by three consecutive months of rainfall above 160 mm each. Unlike other years where such a month was followed by only one month of rainfall above 160 mm and the other months had very little rainfall, generally of less than 100 mm. Having a single month receiving above 300 mm during the rainfall season has only happened five times since 1891, that is in 1893, 1923, 1954, 2006 and 2011 with rainfall amount of 309, 303, 312, 312, 321 mm respectively.

The frequency of such amounts of rainfall per year has reduced from occurring relatively at the interval of 10 years apart to occurring at an interval of 13 years apart, then to 16 years apart, and longer, between the years of 1974–2006. Contrary to the 500 mm amount of rainfall, the occurrence of the rainfall amount less than 200 mm has been more frequent. The events of dryness increased from occurring once in 35 years between 1946 and 1981, to occurring once in 17 years between 1981 and 1998, and then once in 9 years between the years of 1998–2007 and between 2007 and 2016 respectively. This result shows increasing aridity patterns are found within our data. We also observe a large above average precipitation shift e.g., between 1891 and 1962, we have a consistent cyclic rainfall pattern for Windhoek, which slowly breaks down after 1964. The average rainfall for Windhoek is 350 mm per annum. From Fig. 3a and b, we observe that Windhoek has frequently received above 500 mm annual rainfall between 1891 and 1962. After 1962, there is a clear decrease in this pattern as shown by

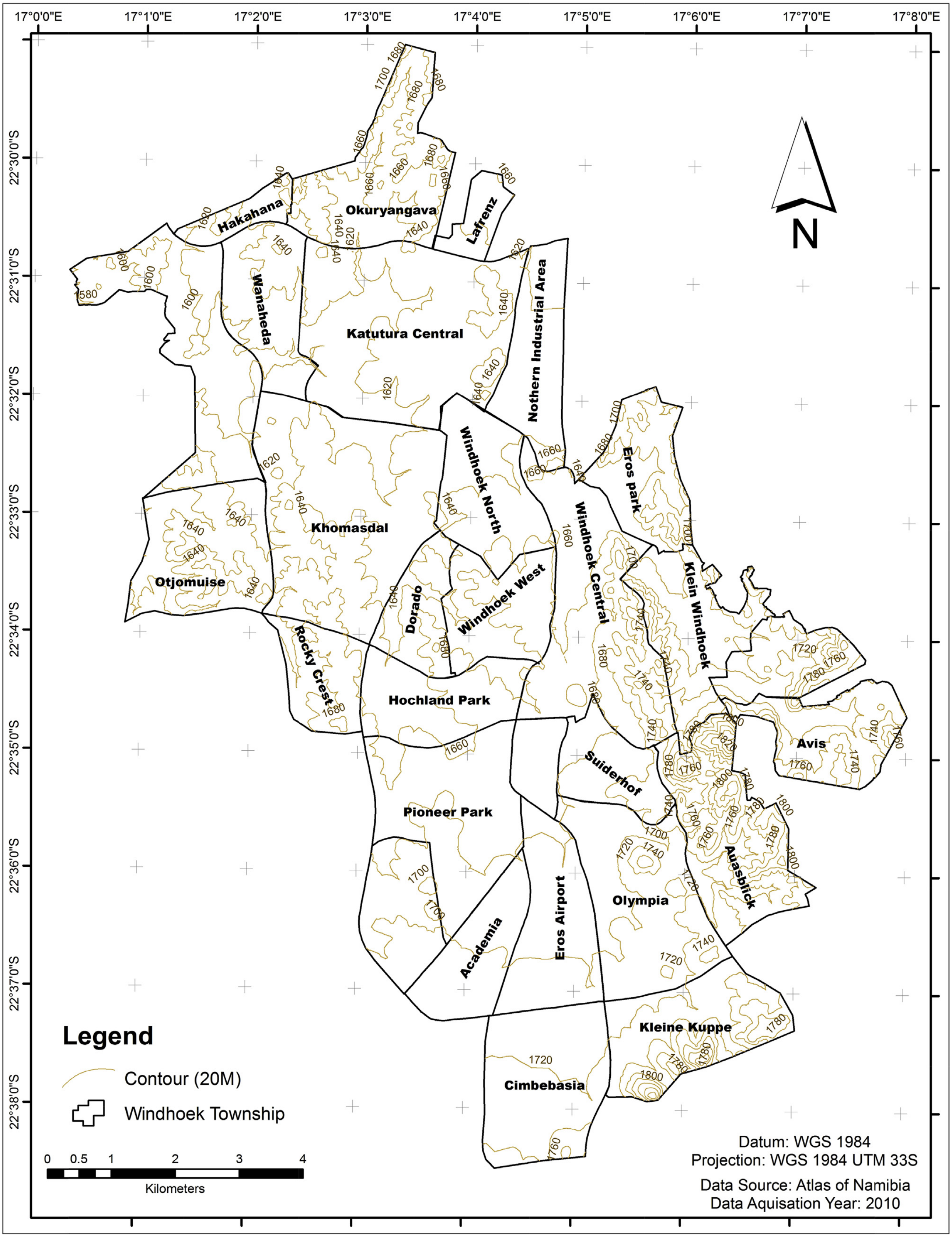


Fig. 1. (*continued*)

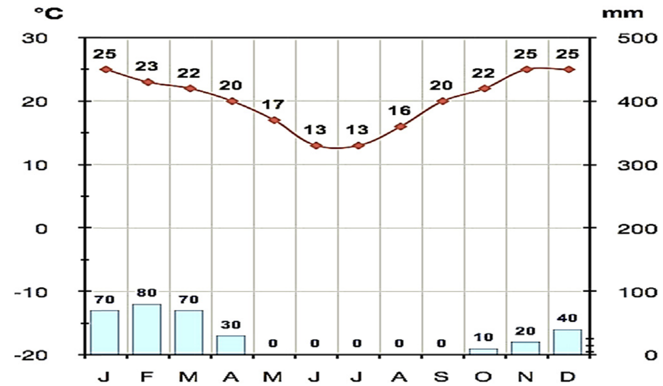


Fig. 2. Monthly average temperature (°C) and rainfall (mm) of Windhoek (GeoKnow.net, 2015).

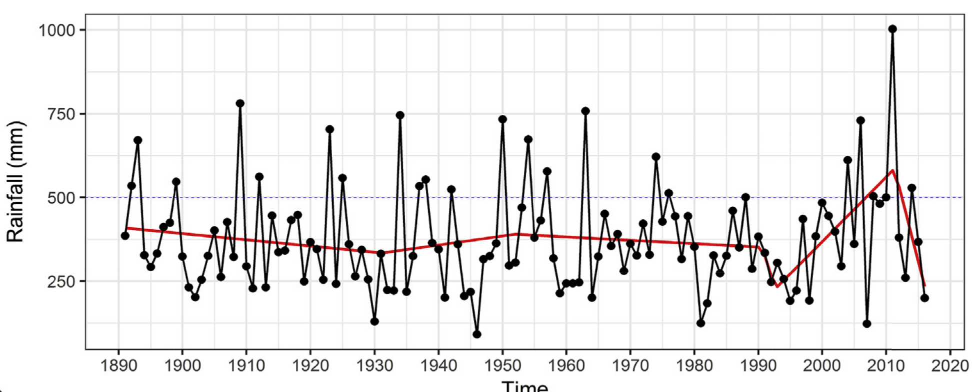
both Fig. 3a and b, and in total annual rainfall from the raw data. This consistent decrease in precipitation formed a large climatic shift in rainfall. This corresponds with the drought periods indicated by the SPI (Fig. 3b). The dotted blue line indicates moderately drought (−1.00 to −1.49) and red dotted line shows severely drought (−1.50 to −1.99). While the SPI shows that the moderate drought periods are common in Windhoek, the test also shows the frequent occurrences of extreme drought (below −2.00) in recent decades, 1983–2007.

Monthly rainfall shows that there is a slight shift on the months receiving more than 200 mm, such that previously the months receiving the most rainfall was January and now it has gradually moved to March (Fig. 4). The rainfall of above 200 mm of has been mostly received in January from 1891 to 1937 while from 1938 to present, it has been received mostly in March. The rainfall received is also not evenly distributed over a month. Most of the months with rainfall above 200 mm have on average a total of four days that received a good amount of rainfall, with one day receiving approximately about 60–70 mm, and another day with around 40 mm, plus around two days with nearly 20 mm each. The rest of the month days are almost completely dry.

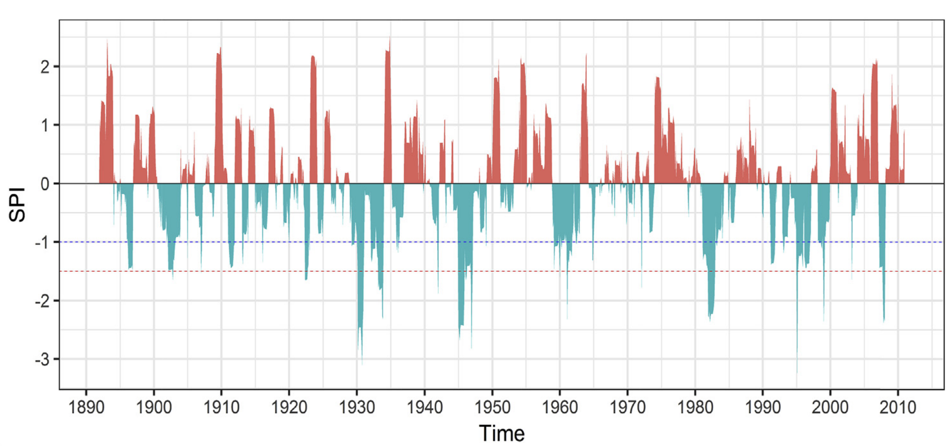
3.2. Future annual trends

Fig. 5 shows the past and future trends. The predictions indicate a general trend of a reduction in rainfall with a few years, 2019, 2022, 2028–2031, 2041–2045 and 2053–2054, with the amount of rainfall being lower than the previous time (Fig. 5). Both periods are also followed by a period of even lesser rainfall (more dry periods), with each period lasting longer each time than the previous time. The total annual rainfall from Windhoek Meteorological station shows an increase in the last 12 years. However, other stations and the overall trend show decreasing tendency. The trendline shows a predicted trend to be decreasing at a faster rate compared to the current rate which is very low. In observed trends, there is almost no decrease from 1945 to 1965, and an overall decrease of only about 50 mm is observed from 1965 to 2016. However, for the estimated period (2017–2060) an overall decrease of close to 125 mm (2,5 times than before) is anticipated (by subtracting the total annual rainfall of 2017 from the one estimated for 2060).

The predominant patterns of the rainfall varied spatially over the city (northern, central and southern) and over time. The northern part



a)



b)

Fig. 3. (a) Mann-Kendall trend test, and (b) Standardised Precipitation Index.

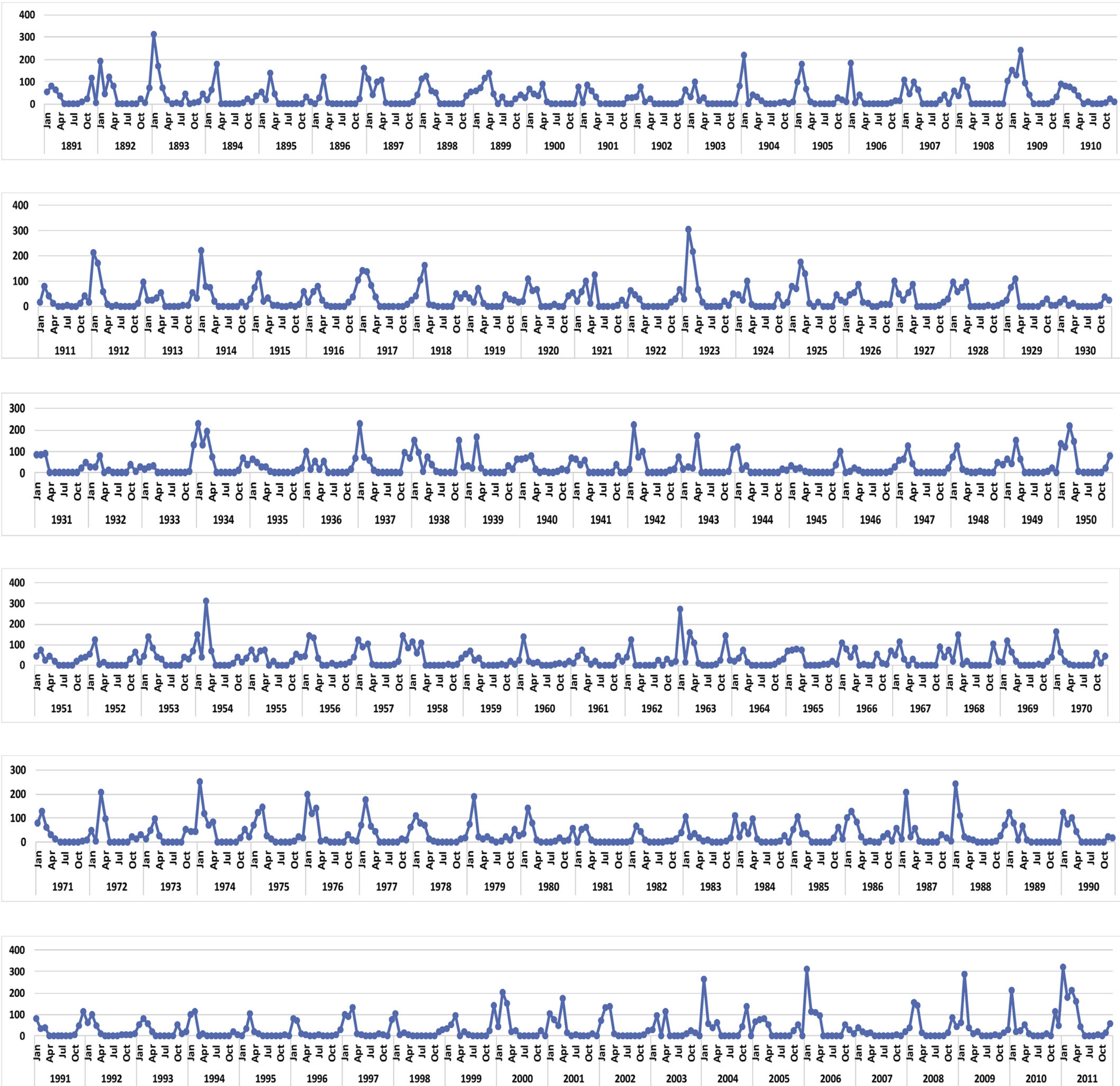


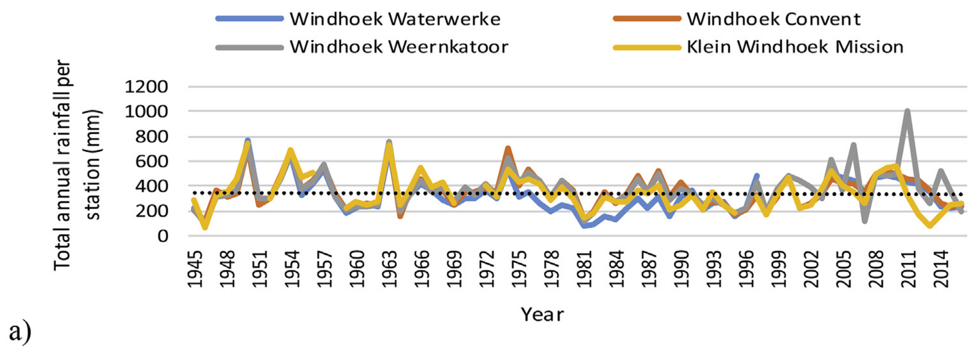
Fig. 4. Windhoek total monthly rainfall (mm) from 1891 to 2011.

has always received less amounts of rainfall (< 260–340 mm) compared to 340–380 mm the rest of the city received from 1945 to 1999 (Fig. 6). The decades of 2000 had the highest average rainfall compared to other decades (2020–2060) for almost the entire city, with almost the entire city receiving an average rainfall of 360 mm–380 mm. This is contrary to the estimated drier conditions over the next four decades (2021–2060). However, average amounts of rainfall of 360–380 mm for the decade of 2021–2040 and 320–340 mm for 2041–2060 is anticipated for areas closest to Windhoek Weernkantoor station. The difference in estimated rainfall for Windhoek Weernkantoor station from Klein Windhoek Mission station is interesting when considering the proximity of two stations (Fig. 1). The former station is built on higher ground with respect to the latter.

4. Discussion

4.1. An overview of rainfall patterns at regional scale

The IPCC report on Climate Change mentions that countries at high latitudes and in equatorial Pacific regions are expected to experience an increase in annual mean precipitation while the annual mean precipitation for counties at mid-latitude and in subtropical dry regions will be expected to decline (IPCC, 2015). The frequencies and amplitudes of precipitation will therefore, be either above or below the standard rainfall of the respective countries (Joubert et al., 1996; Fauchereau et al., 2003). These findings are in accord with our results. The weather patterns from our data set in the last century have more or less followed the sunspot activity on the sun, that is reflected in the data set (The et al., 2005; Bard and Frank, 2006) and has a cycle of 10–11



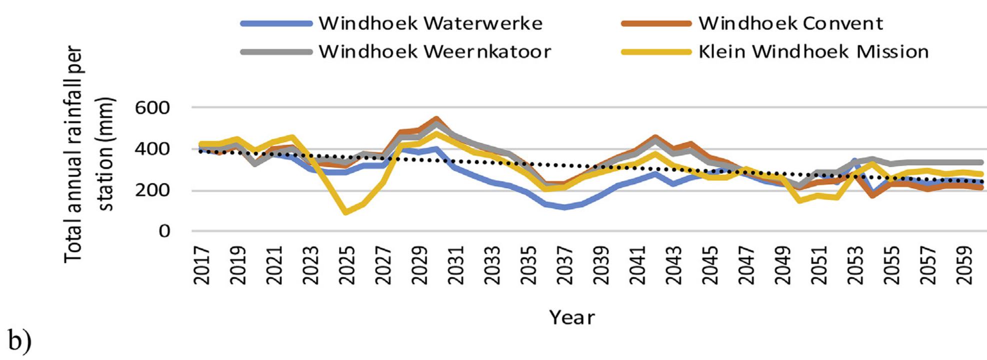


Fig. 5. (a) Past, and (b) estimated total annual rainfall trends based on four stations.

years (Figs. 3–5). This has been observed up to the year 1966. The sudden change and misfit in this pattern has significance in that it shows certain forcing factors, such as anthropogenic activities that promote greenhouse gas emissions have influenced the climate patterns observed on earth (Tans et al., 1990 & Le Quéré et al., 2018). The years 1966–1981 are consistent with worldwide sudden increase in industrialisation, especially that of Europe and North America; and this growth of industries continues steadily up to the present (Roberts, 1987; Tans et al., 1990 & Le Quéré et al., 2018).

The rainfall variability around the world has been investigated and found to be impacted by global warming through the changes in hydrological cycle (Hewitson, 1997; Fauchereau et al., 2003; Shongwe et al., 2009). As a result, the current precipitation patterns are expected to change as well. With specific reference to Southern Africa, projections have not only revealed a decline in rainfall and increased frequency, but they have also showed periods of severe drought in the 21st century (Fauchereau et al., 2003; Engelbrecht et al., 2009). At least a decline of up 5% in the amount of rainfall is expected for Southern Africa region (Hoerling et al., 2006) and at least 10–20% reduction in annual average rainfall is anticipated largely over Namibia, between 2081 and 2100 (Fig. 7).

4.2. Windhoek water crises and anticipated potential times for harvesting rain water

Around 15% of the Namibian national population currently resides in Windhoek and are experiencing the severe impacts of water shortages. The greater part of the population resides on the lower ground where lower rainfall is received compared to the higher ground. The future estimates show a continuation of this trend. The total amounts of annual rainfall below 150 mm are deemed exceptionally dry periods (droughts) but are regarded as normal when occurring once in every 13–14 years (Mendelsohn et al., 2002). Despite the Mann- Kendall trend not finding an outstanding monotonic trend, the total annual rainfall of below 150 mm which has only occurred four times since 1891 (i.e. 1930, 1946, 1981 and 2007, see Fig. 3a) corresponds with the SPI extremely drought periods (Fig. 3b). Even though the 150 mm rainfall values have occurred only four times, the upper end of the scale has however reduced dramatically as shown in Figs. 5 and 6. This suggests that the aridity has been increasing steadily.

Future trends of precipitation are estimated to be gradually reducing with time (Fig. 5). Observations from rainfall records shows that periods of rainfall events above 600 mm are becoming less frequent. Forecasting has further revealed that by the year 2030, the highest total annual rainfall will be below 600 mm, less than 500 mm by 2042 and less than 400 mm by 2054 (Fig. 5). All periods are also followed by period of lesser amount of rainfall. This result corresponds with other projection reports on the decline of rainfall amount of at least 10% (Fig. 7) and severe dry periods as projected by Hoerling et al. (2006). From 2022/2023 each period with lesser amount of rainfall is expected to last longer than the previous period for all the stations. Estimations over the next 44 years indicate that overall, higher rainfall amounts could be expected in 2019, 2022, 2028–2031, 2041–2045 and 2053–2054. These periods would be the best time to harvest rain water that can be used to cover the drier periods. Therefore, it is critical to identify more effective solutions for the city because such higher rainfall years are immediately preceded by periods of drought.

4.3. Potential solutions

Many solutions for Windhoek water problems have been suggested by various scholars, some are being implemented (e.g. artificial ground water recharge and the pumping of water from Tsumeb - Kombat - Grootfontein aquifer) (Tredoux et al., 2009; Lafforgue and Lenouvel, 2015) whereas some have not yet been implemented. These include roof water harvesting, the pumping of water from Okavango river and the use of desalination water (Lahnsteiner and Lempert, 2007; Nashima et al., 2013; Lafforgue and Lenouvel, 2015). While many of them have a lot of advantages, issues such as contamination of the aquifer, distance from Windhoek and cost involved in pumping the water are some of the great challenges for city. With desalination, not only the costs of producing the fresh water is a problem, but there is also a high level of

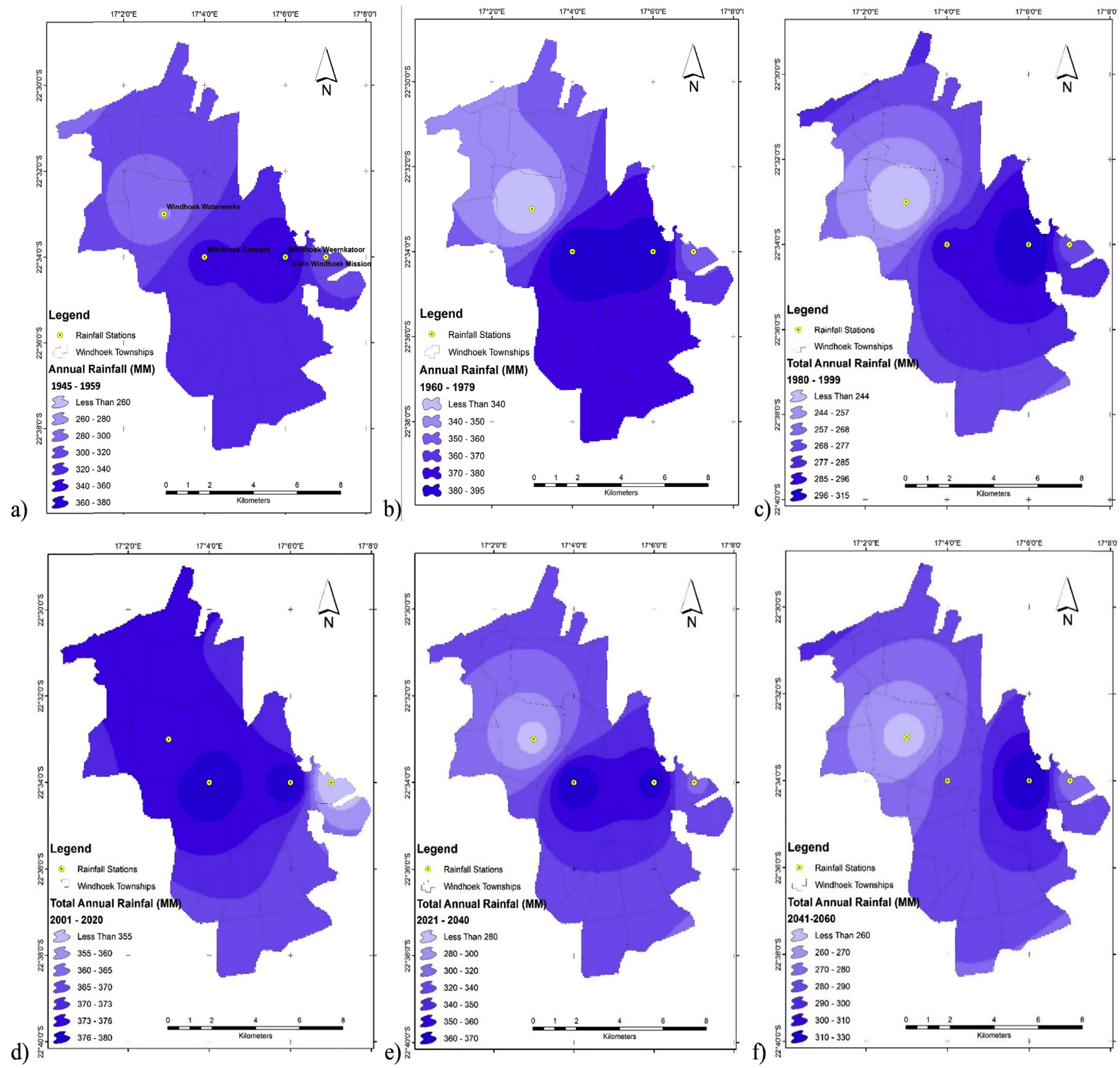


Fig. 6. Past and estimated spatial distribution of Windhoek average annual rainfall.

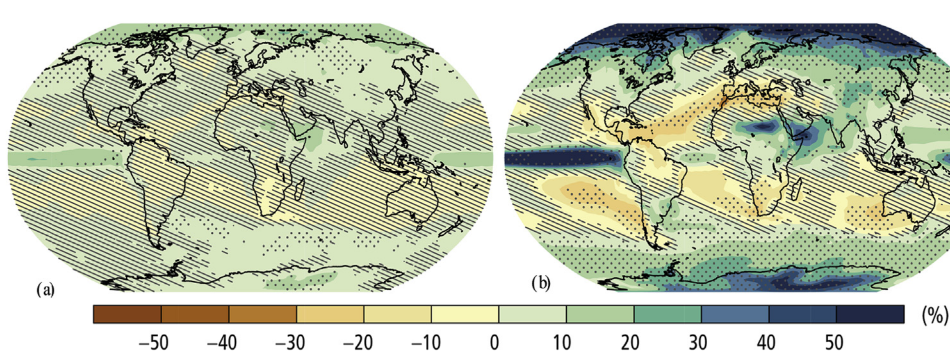


Fig. 7. Changes in average precipitation (a) 1986–2005 to (b) 2081–2100. "*Stippling (i.e., dots) shows regions where the projected change is large compared to natural internal variability and hatching (i.e., diagonal lines) shows regions where the projected change is less than one standard deviation of the natural internal variability*" (IPCC, 2015).

energy needed (Lafforgue and Lenouvel, 2015). Using for instance renewable resources such solar energy maybe a solution to consider. This will not only reduce the costs of energy, but it is also a more lasting solution, making desalination a more permanent solution for the city. However, it is evident that despite the current effort of artificial recharge and water transfer schemes, the water quantity required will continue to rise and these interventions will soon be inadequate.

A more potential and practical proposed alternative is the use of underground water tank system. The study recognises the high costs that the system involves in setting it up properly. However, once set up, the challenges of managing water supply could be minimal. Given the high sensitivity of the semi-arid region, underground water tank system can be advantageous in many ways. With the anticipated increase in temperature in dryland regions, the underground water tank system is not likely to be affected by evaporation as is the case for open dam systems. The system is also convenient for the limited space of Windhoek (a small valley between highly rigid mountains) and the top part of the tank can be habilitated into either a lawn, sport field or lighter infrastructures. Windhoek Convent and Windhoek Weenkatoor stations (where most of the higher rainfall is received) are areas in which the system can be installed. These locations are well fitted with good drainage system that can be utilised for harvesting surface water runoff into underground water tanks. The system has been used in other semi-arid cities such as Mexico City, in Mexico, Pakistan and Southern California (Altaf, 1994; Rodríguez et al., 2004; Townsend-Small et al., 2011).

4.4. Climate change adaptation strategies

The proposed system for water management and planning for Windhoek comes into a more closer focus if we bear in mind the pertinent results of this study, i.e. offsetting climate change impacts on water supply systems for Windhoek. The study has shown that climate change has impacted precipitation natural cycles for the city (Figs. 5 and 6). In Fig. 5, we observed the precipitation variability from 1945 to 1963, where normal precipitation trends gave an average of about 380 mm of rain per year. A drastic drop of closely 20%, from 380 mm to about 310 mm on average occurred between 1965 and 2014, marking a significant period of aridity setting in climate. This decrease is also further reflected in our estimated data from 2017 to 2060, where the average rainfall will dwindle from 310 to 220 mm part per million. These effects of climate change will require the adoption of resolute and functional mechanisms to harvest rainfall in good years.

5. Conclusion

Due to the high population pressure and its demand for water consumption, it has become significantly difficult to sustain water supply for the city of Windhoek. This challenge is likely to worsen if precautions are not established well in advance. Knowledge of timelines for high rainfall amounts and the extent of dry periods are necessary to help the local authorities in planning for water supply. This study reported on the period from 1891 to 2060. The study has identified the nature of precipitation variations for the future periods of concern for water scarcity using a modelling system in ArcGIS, and the geographical parts of the city that be likely to be affected.

The water scarcity is as a result of climate change due to anthropogenic effects around the globe. The changes in climate has induced a shift of the rain season, forwards by at least one and half months. This is coupled by a decrease in the consistent daily rainfall and instead there has been an increase in extreme precipitation events. These extreme events are characterised by intense periods of rainfall separated by longer periods of drought within a given month. The study has estimated that for next decades, the city will be faced with periods of water shortages that could last more than four years. Thus, there is an urgent need to prepare the city to deal with these expected water crises, as this will not only be a problem for developmental activities, but it is likely to undermine the basic human rights for the inhabitants.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.pce.2019.03.005.

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