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Impact of Climate Change on Spatial Planning and Stormwater Management for Greenfield Site Development

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ABSTRACT

Climate change is indisputably recognised as one of the major global concerns which has multiple negative impacts. Projected climate change impacts such as increased droughts, more intense precipitation and rising sea levels suggest that human goods and lives will be adversely impacted through increased flood risk, among other impacts. Consequently, this study aimed to adapt the current spatial planning principles to address and mitigate the impact of climate change in an urban setting by integrating stormwater management practices. Statistical methods were used to extend the available historical rainfall data to predict the likely frequency of future rainfall events. Autodesk Civil 3D Storm and Sanitary application enabled the simulation of the impact of future rainfall over greenfield sites development.

Flood frequency analysis was conducted as a direct method of estimating flood frequency, indicating that a 21% increase would be expected between the 2020 and 2069 period with the intensity of a 2-year return period expected to increase by 40%. The simulated changes in precipitation were incorporated into spatial planning by using catchment characteristics to derive key land-use zoning factors for future consideration when designing urban areas. The analysis of the study revealed that the amount of greenfield area that is available for stormwater management should be identified at an early stage in project planning. This analysis will largely dictate the extent to which different stormwater design elements are feasible in any development to ensure that climate change impacts are considered. This study provided a methodology to determine the impact of climate change on future rainfall events over greenfield sites for pre-development and post-development conditions. Outcomes of this study may aid in understanding the increasing frequency and intensity of extreme rainfall events, which will have a significant impact on existing stormwater infrastructure. The study may aid Provincial and local municipalities to adapt to changing rainfall regimes to ensure that adequate levels of spatial planning for greenfield sites are effectively integrated with stormwater management to ensure that climate impacts are accounted for prior to any development.

INTRODUCTION

The sequels of climate change are bestowing on humanity great tasks when planning future cities. Climate change is increasingly recognised as a developmental challenge and an impediment to achieving the United Nations 2030 Sustainable Development Goals worldwide (Rosa, 2017). Climate change exacerbates stormwater issues due to the dual impacts of mean sea-level rise and intense precipitation. Climate change, however, has been part and parcel of the occurrence of extreme events in the world (Mann & Gleick, 2015). Strong scientific evidence highlights that the recent climate changes are likely attributable to human activities and the increase in greenhouse gas concentrations in the atmosphere. Greenhouse gases play a vital role in regulating the 'Earth's climate. The substantial increase in atmospheric carbon dioxide over the last 100 years, which increased by over 35%, is believed to be induced by anthropogenic activities (Hulley et al., 2008). The anthropogenically forced global warming and the associated trends in increased temperature result from the enhanced greenhouse effects through which atmospheric greenhouse gas emissions are increased. The most vital concern over climate change's effects on stormwater management is its effects on precipitation.

The increase and intensification in precipitation have put a strain on urban drainage infrastructure (Embertsén, 2012). Africa remains one of the most vulnerable continents to climate change and its impacts. An emerging commonality is a shift towards more intense rainfall. The rainfall arrives in shorter bursts, causing more run-off and dry seasons in between. Although some parts of Africa will experience extreme droughts, some parts will experience extreme rainfall. The global annual average temperature will rise by 1.4 - 5.8°C by 2100, increasing global warming over continental landmasses and higher latitudes. This suggests that it is highly likely that more intense precipitation events will occur in many areas of the world under climate change (Cooper et al., 2002). In November 2016, natural disasters such as flooding resulted in enormous destruction to infrastructure resulting in property damage, strain on stormwater infrastructure and fatalities in one of South Africa's urban areas (Mbangeni, 2016). Land-use changes have resulted in tremendous challenges in designing and implementing stormwater management systems. New developments are at risk of climate change impacts if old spatial planning policies coupled with traditional stormwater management systems continue to be used.

In a study conducted in Sweden by (Cettner et al., 2013), it was highlighted that there is a significant gap that exists between spatial planning and stormwater management planning. Traditional spatial planning approaches mainly focus on zoning areas based on land use, economic explanation of population density but largely disregard stormwater management in urban drainage systems. Thought must be given to the adaption measures for spatial planning to incorporate stormwater management experts to consider climate change effects such as flooding of urban areas for sustainable urban development. Adaptation measures when developing new greenfield sites have been considered one of the solutions to alleviate the detrimental effects of climate change (Demuzere et al., 2014). (Serfontein & Oranje, 2008) evaluated the spatial planning in the City of Tshwane Metropolitan Municipality in South Africa. They identified a profound disconnection between the planning, thought process and the emerging spatiality of the 21st century. They concluded that this was due to the persistence of how planners interpret and act upon space in a manner still based on the nineteenth-century industrial cities. (Mlambo, 2018) has highlighted that some of the internationally identified principles for new urban planning spaces are also applicable to spatial planning in South Africa.

Spatial planning plays a very important economic and social role. However, planning the infrastructure for spatial developments remains the key role in ensuring that planning remains effective and efficient (du Plessis, 2014). The two roles must be strategically planned simultaneously to ensure a sustainable integration between infrastructure development and spatial planning. Spatial planning is a significant area of land use planning and a crucial tool in achieving sustainability, development, and climate change adaptation strategies in urban areas. It is crucial to ensure that every sustainable urban development plan has an accepted infrastructure implementation plan for the area which can be implemented.

The main motivation of this research aimed at determining the impact of climate change within an urban environment by predicting future flood events that are likely attributed to climate change for future consideration over new developments on existing greenfield sites. Innovative considerations are required to be made regarding spatial planning of greenfield site developments to mitigate climate change impact on stormwater management. This research combines spatial planning and engineering concepts in stormwater management, considering climate change as an integral part of integrated stormwater management.

1. MATERIALS AND METHODS

1.1 Location and climate

Roodekrans 492-JQ (study location) is situated within the Gauteng province, west of Pretoria in The Crocodile West and Marico Catchment. Geographically, it lies between 25.855° S and 27.948° E. Roodekrans 492-JQ is situated in a humid subtropical climate with temperatures that vary average of 18.7 °C annually with summer rainfall season. Rain events typically occur in the afternoon between October and April months. Rainfall seldom occurs during winter. The current annual average rainfall is 732 mm, mostly during the December, January and February months.

Roodekrans 492-JQ, previously zoned as a peri-urban development in 1975, is boarded by Hennopsrivier 489-JQ and Riverside Estate 497-JQ located in the South-Western area near Hartebees Dam in the City of Tshwane Metropolitan Municipality as presented in Figure 1. The location has been purposefully selected because of its potential for growth development in the country in terms of urbanisation. The total land surface area is 38 km^2.

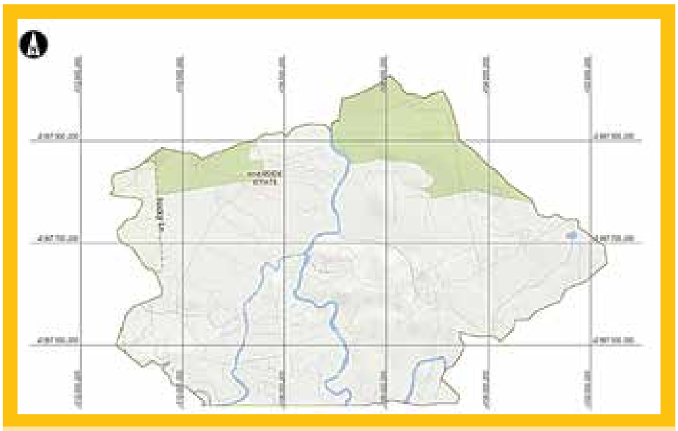

FIGURE 1: Catchment for selected study location (Roodekrans, 492 JQ)

1.2 Rainfall data and topographical data

The daily rainfall at station number 6 545 weather station for the Pelindaba gauging station was obtained from the South African Weather Services. The daily rainfall (mm) data, for the years 1969 to 2019 (51 years) for Roodekrans 492 JQ were obtained. The maximum annual daily rainfall (MADR) event was extracted for each year. The Roodekrans 492 JQ intersects by the Hennops River, which rises to approximately 1530 metres above sea level (m.a.s.l) near Atteridgeville, far west of Pretoria. The United States Geological Survey (USGS), provides users with various Data Elevation Models (DEM)s. The GDEM model was downloaded, and Hexagon Geospatial provided GIS tools to retrieve the topographical information. This information was transferred to Autodesk Civil 3D Storm & Sanitary Analysis tool software package for hydrological modelling. The GDEM was used for hydrological modelling purposes. From the Geo.tiff image, we developed a raster image for visualising the topographical data and subsequently generated it to develop the hydrological model.

1.3 Land cover and land use typology

It is crucial to understand the characteristics of the spatial distribution of South Africa's land cover. Landsat images were downloaded from the USGS Earth Explore together with the DEM files. Landsat 8 Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS) images consist of nine spectral bands and two thermal bands. The Landsat images loaded into Erdas Imagine to further develop the image. The Landsat was georeferenced to the WGS 84 coordinate system. The classification complete after the different bands were stacked to develop one image in which classification was performed to identify soil, vegetation, and water classes based on the spectral reflectance soil, vegetational and water. The Roodekrans current land use satellite image detection Landsat thematic mapper (Landsat 8) which shows the current land properties of the study location.

1.4 Frequency analysis of annual maximum events

Stochastic methods or frequency analysis can be used to evaluate peak flows where satisfactory measured streamflow information exist. The frequency analysis was conducted to determine the appropriate probability distribution function (PDF) for the extreme events between 1969 and 2019. The Annual Maximum Run-off events (24 hrs) for the selected period were determined. The probability of exceedances (p) of Annual Maximum run-off events was determined by ranking the largest Annual Maximum run-off events to the smallest.

The Weibull formula was applied to determine the estimates of exceedance probabilities associated with historical rainfall observations, as shown in Equations 1 and 2.

$$p = \frac{i}{n+1} \qquad \text{Equation 1.}$$

$$T = \frac{1}{1-p} \qquad \text{Equation 2.}$$

Where:

P = Exceedance probability associated with a specific observation.

N = Number of annual maximum daily events (51 evens in this case);

x = Observed rainfall (mm)

i = Rank of specification observed event with i = 1 being the largest event to i = N being the smallest event

T = Return period (T) of each event is the inverse of its exceedance probability. **Equation 3.**

1.5 Selection of suitable probability distribution function for the study area

The maximum annual rainfall selected for this study area involved estimating the distributions selected and identifying the best distribution model suited for estimating extreme hydrological events for the study area. To estimate the maximum annual rainfall quantiles, the PDF that suits the said events had to be applied (Masereka et al., 2018). The three goodness of best-fit test, which was tested and then applied, were the chi-square test, Kolmogorov-Smirnov test, and the Anderson-Darling test. Through identifying the best-fit PDF models for our sample, we were able to identify the best fit model for our data. The selection of an appropriate model depends mainly on the characteristics of available rainfall data for a particular study area of interest. A PDF that provides a good fit to daily precipitation depth is key. Therefore, for this study, the PDF model was analysed for the current data to determine the best fit model for the current data of our study area. For this study, different PDF types such as Log-Pearson Type III, generalised extreme value, Weibull and Gumbel were assessed to find the best fit PDF for maximum annual extreme rainfall. This was done to visually identify the candidate PDFs for analysis of magnitude and frequency of analysed extreme events. (Masereka et al., 2018) identified a method of identifying the best fit, which was subsequently used for this study. The PDF selected for this study was Gumbel's distribution.

1.6 Forecasting precipitation for the 50 years (2020-2069)

The technique used for the forecasting of the next 50 years of rainfall was under the assumption that the future rainfall series will indicate similar trends as the historical series. The technique applied simulates the historical series by identifying a specific pattern in the series to predict or simulate the historical pattern into the future without trying to understand the causes or effects of the historical patterns. The analysis from the previous sections was repeated for the forecasted data with the assumption that the selected PDF would be suitable in assisting to predict the future causes. The Gumbel's Extreme Value was selected as the best PDF for the historical data analysis. Therefore, the calculation for the maximum extreme discharge recurrence interval for the different return period was determined using the Gumbel extreme values. The PDF for Gumbel's distribution is given as follows:

$$F(x)' = exp[-exp\left(-\frac{x-u}{a}\right)] \qquad \text{Equation 4.}$$

The following equations were used for Gumbel's Extreme Value calculation;

$$P' = e^{-e^{-y}} \qquad \text{Equation 5.}$$

$$y = -(ln\ x\ (ln\left(\frac{T}{T-1}\right)) \qquad \text{Equation 6.}$$

$$T = \frac{1}{1-P_r} \qquad \text{Equation 7.}$$

Where:
P' = probability of non-occurrence of an even X in T year
y = reduced variate for a given T
y(n) = reduced mean using (Gumbel's extreme-value distribution)
s(n) = reduced standard deviation using Gumbel's extreme value distribution)

To determine the frequency of the highest extreme events for the forecasted events, it was established that;

$$x(t) = `x + K\sigma_{n-1} \qquad \text{Equation 8.}$$

$$\sigma_{n-1} = \sqrt{\frac{\Sigma(x-`x).^2}{N-1}} \qquad \text{Equation 9.}$$

$$K = \frac{(y(t)-y(n)}{s(n)} \qquad \text{Equation 10.}$$

Where:
σ = standard deviation of the series
K= frequency factor
N = Number of years of record

1.7 Impact of climate change

The extreme events were determined and applied to a hypothetical example. A hydrological simulation was conducted over the study area to assess the different simulation results to assess the impact. The peak flows were determined for both pre- and post-development for each scenario selected for this study. In this study, the catchment was split based on basin characteristics. This was done to determine the extent to which land-use planning (zoning) conditions can impact the stormwater management of the catchment. Also, the 50-year projection or scenario is based upon assumed trends and changes in fertility, mortality, migration and productivity in urban areas. The model simulates different stages of annual average rainfall over three (3) different climate categories to indicate the exact changes in annual rainfall generation.

1.8 Simulation of stormwater generation for different future climatic conditions

The rapid increase in development contributes to increased non-point source pollution and degradation of receiving waters. For the study, we introduced pre-development conditions and post-development scenario for historical and forecasted rainfall trends. To facilitate the hypothetical catchments management of the study area, the area was divided into different sub-catchments to understand the full impact of the simulated rainfall over the study area and its impact on the stormwater run-off. The catchment was delineated based on the DEM to create 13 sub-catchments with an average area of 100 hectares. The pre-development scenario represented the existing conditions of the study area, which is currently a greenfield site with very little development. The sub-catchment areas were used for surface analysis and were found to resemble similar natural catchment areas as derived from historical topographic maps.

The area reduction factor was applied for the different return periods, namely 1:25 and 1:50 year. The equation applied was as shown in equation 11.

$$ARF = (90000 - 12\,800lnA + 9830\ln(60T_c))^{0.4} \qquad \text{Equation 11}$$

Where:
ARF = site area reduction factor
A = catchment area (km^2)
Tc = time of concentration (hours)

1.9 Post-development conditions

The post-development conditions were determined solely for this study to understand the impact of climate change on land-use developmental conditions. The sub-catchment characteristics were revised to determine the peak discharge when the area has been developed.

Surface Run-off Analysis

In South Africa, there are different methods available to determine the normal stormwater run-off. The Rational Method, Standard Design Flood (SDF) Method and the Alternative Rational Method can determine design floods at various points within the area to estimate the overall surface run-off. In order to calculate the peak surface run-off, the Alternative Rational Method was used, and the Standard Design Flood methods were used to calibrate the results. The flows were determined for a daily extreme rainfall event through the frequency analysis and PDF selections. Peak Flows for the 1:25- and 1:50-year extreme rainfall events were calculated for the selected catchment and each sub-catchment.

Alternative Rational Method

The alternative rational method was used for determining the peak surface run-off flows for the study area. This method is based on the rational method, with the point precipitation being adjusted to account for local South African conditions. The representative rainfall is available from the TR102 However, the frequency analysis was conducted for the historical data, and the daily rainfall for the required return periods was established. This information can be used to calibrate the hydrological model. To determine the rainfall intensity for the study location, the Alternative Rational Method uses the Hershfield Equation. The modified Hershfield method of estimating point rainfall is a very useful and reliable tool for hydrological designs. It is mainly based on the analysis of a vast amount of rainfall (Koutsoyiannis, 1999). To determine the point rainfall for the specific return period the Hershfield's equation was used in Equation 12.

$$P_{i(T)} = 1.13(0.41 + 0.64lnT)(-0.11 + 0.27\ln(t))(0.79M^{0.69}R^{0.20})$$

Equation 12

Where:

Pi(T) = rainfall depth for duration of t and return period of (T) years in (mm)

t = duration (minutes)

T = return period

M= 25- and 50-year return period (GEV)

R = average number of days per year on which thunder was heard (days/year) obtained by establishing the study area's position.

1.10 Incorporation of the simulated climatic variation into land-use planning.

Storm & Sanitary Analysis (SSA) program has various relevant deterministic, statistical and empirical methods which the user can incorporate for their designs. The catchment was partitioned into 13 sub-catchments, and their effective areas were also determined based on the current natural sub-basin. To conduct a hydrological model for the study area, the different sub-catchments were thus given hypothetical land development conditions. These land conditions were introduced for all three (3) scenarios (base, historical and future climatic conditions). The hydrological model was simulated using the Rational Method to determine each sub-catchment peak flows. The following equation explains the rational method:

$$Q = \frac{CIA}{3.6} \qquad \text{Equation 13}$$

Where:

Q = Peak flow for the given return period (m^3/s)

C= Run-off coefficient given by the catchment characteristics

I = rainfall intensity for the study area (mm/h)

A = Effective Area (km^2) as calculated in Equation 13 above.

The pre-development conditions were determined using the current state of the catchment characteristics. The post-development conditions were hypothetically determined to understand the impact of the point rainfall over the catchment area and, subsequently, its impact on the overall climate change findings. The different sub-catchment was hypothetically zoned to quantify the overall surface run-off should the area be developed.

The base, historical and forecasted point rainfall were all analysed for pre- and post-development conditions. This was done to understand the impact of climate change determined over the study location. The base and historical scenario used was for 1969 to 2019, and the future conditions used was for the 2020 to 2069 period. Land clearing can lead to soil degradation and massive erosion during rainfall events (Busayo et al., 2019).

RESULTS & DISCUSSION

2.1 Rainfall data and topographical data

Rainfall Data

The daily rainfall at station number 6 545 weather station for the Pelindaba gauging station is illustrated. The mean annual rainfall series for the Pelindaba gauging station exhibits significant seasonal variations. This can be attributed to climate variations for each year. The increasing trend of Spring rainfall is statistically insignificant since the coefficient of variation of (47.3%) for Summer rainfall is higher than that of Spring rainfall (39.9%) which implies more interannual variability of Summer rainfall than the Spring rainfall.

The mean annual rainfall of the area during the study period was 64.8 mm with a 21.97 mm standard deviation. The highest mean annual rainfall event was 139.8 mm, which was experienced on the 25th of March 1995, and the second highest was 115.8 mm, which was experienced on the 2nd of February 2014. In the study area, summer is the major rainy season, contributing about 34.6% of the total rainfall (where over 30% comes only in two months: December and January). In contrast, February contributed 3.6% of the summer rainfall. The short rainy season, which lasts from September, October and November (Spring season), also contributes a considerable rainfall (around 27%) of the total maximum annual rainfall. Since the maximum average annual rainfall was experienced in 1995 and 2014 (almost 20 years apart), the rainfall data for the period (1969 to 1995) was compared with the rainfall data for the period (1996 to 2019). The results indicate an 8% increase in annual mean rainfall and 10% rainfall for the Summer season. For instance, the mean annual rainfall and the Summer rainfall (December to February) in the study area from 1969 to 1995 were 60.6 mm and 27.5 mm. This amount had increased to 69.3 mm and 38.9 mm during 1996–2019 for both annual and summer season, respectively. The linear regression model of the data indicate the rate of change, which in the three cases is +0.0498 mm/year, +0.028 mm/year and +0.0282 mm/year for annual, Summer and Spring rainfall respectively.

The mean annual rainfall and summer rainfall has increased, on average, by 8.7 mm and 11.4 mm, respectively, over the past 25 years compared with the period between 1969 and 1995. We can conclude that an extension of the rain season is likely to occur in early spring, with an increase in rainfall predicted for September, October and November. The number of rain events is expected to increase, which could conclude that the chances of floods may increase based on wetter antecedent conditions attributed to climate change. There is an existing relationship between rainfall and run-off, as it is evident that the increase in rainfall is expected to impact the existing stormwater infrastructure. Increases in future rainfall due to climate change in combination with sea-level rise could cause flooding in stormwater drainage infrastructure. More stormwater overflows can be expected with the increasing stormwater volumes, which will exacerbate the existing infrastructure. The amount of water generated within a catchment steadily increases with sprawling development. The amount of run-off volume will be dependent on the urbanisation of areas. Therefore, it is prudent that the development of greenfield sites considers the increase of rainfall to manage stormwater within the catchment area.

Topographical Data

The Roodekrans 492 JQ intersects by the Hennops River, which rises to approximately 1 530 metres above sea level (m.a.s.l) near Attridgeville, far west of Pretoria. The elevation variation over the study area, which ranges between approximately 80 meters (m.a.s.l) towards the west and approximately 155 metres (m.a.s.l) along the south-eastern boundary of the study area. The high interior highland and the low-lying region have relatively steep terrain, while the ridge zone has flat rolling terrain with smooth valley flanks. The study area generally slopes from the northwest to the east. Slope analysis of the catchment area was within the 3% to 20% gradient range. Small isolated areas reached a maximum gradient of 30% along the lower edges of the catchment area. The basic statistical analysis of the rainfall in the study area revealed that it is evident that rainfall in the selected study area is predicted to increase over the upcoming years. The majority of the increased rainfall that is projected is expected to occur during the summer months. The chances of flooding in the area are thus higher due to the fairly flat topography, which does not encourage natural surface flow. Should any development occur, it will interfere with the run-off patterns.

2.2 Land cover and land-use typology

From general observation of the land cover for the study area, a significant proportion of the land remains undeveloped. Satellite images and the subsequent thematic maps extracted from available sources such as the USGS are crucial for environmental protection and spatial planning. The image classification process involves converting multi-band raster imagery into a single-band raster with different categorical classes related to diverse land cover types. The study area is predominantly made up of greenfield areas. The study area is characterised by agriculture (cultivated land, plantation areas, pasture, dryland). It is also characterised by mining and a small fraction of industrial activities. The northern and southern portions have been intensively mined over the years. Private agriculture also predominates. The greenfield area is in the vicinity of the Hennops River. Land use plays an important role mainly because of the effect of the infiltration rate; therefore, present and future conditions should be properly taken into account, especially regarding urbanisation.

2.3 Frequency analysis of annual maximum events

The historical data collected for this study indicate that most of the increased rainfall projected is expected to occur during the summer months, namely December, January and February. An extension of the rainy season may occur in early spring, with an increase in rainfall predicted between September to November (CSIR, 2019). The statistical analysis of this study indicates that the number of rain events is expected to increase, which could conclude that the chances of floods may increase based on wetter antecedent conditions and increased urban developments. The rainfall data were patched using the linear regression patch method. The descriptive statistical results derived for the Maximum Annual Rainfall data indicate the mean of 64.88 mm, which is larger than the median at 63mm with a positive skewness of 0.909 and the data had a tail that was on the right. The statistical results also show that the sample data is far from normal distribution, reflected in kurtosis, which is at 15.802.

Evaluations of the risks of extreme weather events such as heavy rain require methods to statistically determine their return periods from existing measured data. The ranking and plotting positions have gone under mathematical analysis, such as the Gumbel 1958 plotting method, so that the theoretical practicalities are understood in principle. The equations were used to determine the relationship between the plotting positions representing the Maximum Annual Rainfall events for the historical rainfall data. These return periods have been selected because stormwater drainage systems are generally designed for the 1:50 and 1:25 year design period. The results indicate that the probability of an extreme event for the 1:50 years and 1:25 years selected for this study is approximately 139.8 mm and 115 mm, respectively.

The Gumbel's distribution was selected as it is mainly used to analyse extreme values and survival analysis. The different plots were developed to identify the best PDF for the study area's rainfall data. Only the three distribution functions were assessed. From Figure 2, we can observe that the Gumbel distribution function, together with the other two distribution functions, followed a similar trend to the linear plot. The data for the PDF should have fallen on a single line inclined at 45° to the axes. The data demonstrate some scatter, but the band in which all the data are plotted can be considered reasonable. This shows that the prediction by the present method compares favourably with the Gumbel method. This representation of the results indicates that the Gumbel distribution method is the best representation that can be used to estimate the values corresponding to any return period, namely 2-, 5-, 10-, 20-, 25-, 50- and 100 years. The Gumbel distribution represents the rainfall data received better than the other two methods, namely, Weibull and Log-Pearson Type III.

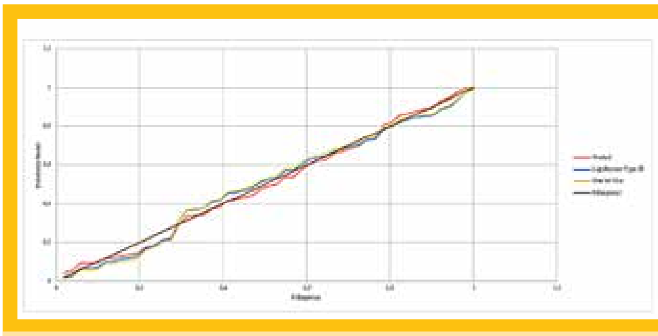

FIGURE 2: Probability distribution plot of maximum annual rainfall events for the Roodekrans area (1969 to 2019)

2.4 Selection of suitable PDF for the study area

The PDFs were selected based on their ranking. The PDFs selected were Gumbel, Log Pearson Type III and Weibull, closely following the theoretical PDF trendline. The Gumbel distribution function closely follows the theoretical estimates for the rainfall data's maximum annual rainfall events. Quantile fitting of distribution for the Maximum Annual Rainfall series for the data, which has computed the theoretically expected value for each data input. The quantile plot demonstrates that the data follows a fairly normal probability distribution except in the extreme ends, for example, the 1:100-year return period.

With this information in hand, we can determine the return periods for the data received using the Gumbel distribution method to further determine the magnitude events used in stormwater infrastructure design. Among the PDFs presented in this study, the Gumbel distribution function yielded the best-fit PDF. The PDF yielded the best fit as presented in this study. For this study, the Gumbel distribution was selected. The Gumbel distribution function. It should be noted that rainfall data received has only 51 years of rainfall data available, which unavoidably yields much lower confidence in the results as the return period increases. For this study, the 1, 2, 5, 10, 20, 25 and 50-year return periods were assessed. Quantile plots curve follows the distribution very well for lower daily rainfall then drifts away from the theoretical distribution at extreme rainfall returns. The data also shows that longer return periods have more uncertainty around the quantile estimates. The selection of the probability of exceedance is also related to the risk that one is willing to accept and the project's lifetime.

2.5 Forecasting precipitation for the 50 years (2020-2069)

The Gumbel (Generalised Extreme Value Type I) distribution function was selected for the data. We were then able to derive the return levels of extreme annual maximum rainfall. The T year return level is the level that exceeded on average only once in T years. The return level for 2, 5, 10, 15, 20, 25, 50- and 100-year return levels are indicated in Table 1. We were then able to forecast the values for the period 2020-2069. From the values, we could see the climate impact for the next 50 years, which indicated that the

TABLE 1: Return level of maximum extreme rainfall (mm)					
T (return period)	yt	K	1969 to 2019 (mm)	2020 to 2069 (mm)	Climate Change Impact
2.00	0.366513	-0.15692	61.4281	86.33431	40.55%
5.00	1.49994	0.81824	82.85328	105.4584	27.28%
10.00	2.250367	1.46388	97.03861	118.1203	21.73%
15.00	2.673752	1.828144	105.0419	125.264	19.25%
20.00	2.970195	2.083193	110.6455	130.2658	17.73%
25.00	3.198534	2.279647	114.9618	134.1185	16.66%
50.00	3.901939	2.884831	128.2583	145.987	13.82%
100.00	4.600149	3.485545	141.4565	157.7678	11.53%

expected average was a 21% increase in the rainfall frequency to be expected overall. The results demonstrate that rainfall is expected to increase over the study area under future climate change scenarios. The increase is estimated at 40% for a 2-year return period and 11.53% for a 100-year return period. This equates to an increase in rainfall of between 20% and 40% by 2070. These results suggest that precipitation will become more intense and more frequent over time. The results depicted the 2, 5, 10, 20, 25, 50 and 100-year return periods. Using the Gumbel distribution function for 50 years shows that we would anticipate that the average monthly rainfall will increase by 13.82%. This can develop more detailed risk and damage estimates such as flooding levels and stormwater infrastructure damage.

2.6 Simulation of stormwater generation for different future climatic conditions

Three scenarios selected were namely, the base, historical and forecasted scenario. The base scenario was extracted from the TR102 data as provided by the South African Weather Services for the daily rainfall. Daily design rainfall was determined using the frequency analysis for the scenario 1 (1969 to 2019 - historical) period and the scenario 2 (2020 to 2069 - forecasted) period. These data sets were used to calculate peak flows for the catchments within the Alternative Rational and SDF methodologies. The extreme rainfall events for the three (3) scenarios. The extreme rainfall depths are representative of the extreme daily event over the catchment.

2.7 Catchment characterisation and hypothetical land use development conditions

The catchment was delineated based on the DEMs to create 13 sub-catchments with an average area of 3 square kilometres (km^2). The pre-development scenario represented the existing conditions of the study area, which is currently defined as a greenfield site with very little development. The hypothetical zoning conditions were subjected to the hydrological scenarios developed for this study. Each daily rainfall for the applicable periods was considered to determine the run-off for the entire study area.

This analysis will provide insight into the impact of the development over the study area for each of the scenarios selected for this study. The hypothetical examples were subjected to peak run-off calculations for both the pre-development and post-development conditions. This was to understand the pre- and post-development run-off. The current daily rainfall, the base scenario, is modelled as received from SAWS TR102 systems. Historical scenario (scenario 1) used historical rainfall data to develop a theoretical PDF to predict future development conditions by using frequency analysis. The forecasted values, scenario 2 (forecasted scenario), indicate the future rainfall conditions that may need to be designed. The impact of future rainfall may be severe. Thus, looking into the urban developmental conditions will assist in understanding developmental conditions on stormwater management and how to strategise for this. To assess the response to daily flow indices to land-use changes and the impact of climate change, the daily flows were simulated by changing the land use under specific climate conditions.

2.8 Pre-development and post development conditions

The pre-development conditions of the study area consist of mainly. It is also characterised by mining and a small fraction of industrial activities. The area has thus been sub-divided into different sub-catchment areas based on the current flow characteristics of the natural ground. The pre-development characteristic assumptions were based on the existing site conditions and measured properties. The general slope of the site is 3%, of which the area is mostly naturally landscaped, which encourages permeability. The vegetation and land characteristics of the area were used to determine the coefficient characteristics to determine run-off. The overall elevation throughout the site varies between 80 metres (m.a.s.l) towards the west and approximately 155 metres (m.a.s.l) along the south-eastern boundary of the study area.

These are critical elements to determining the stormwater run-off for the study area at its pre-development state. The post-development conditions (catchments characteristics) were based on the proposed development conditions for the study area. The proposed development consists of 4 different development conditions based on the post-development characteristic assumptions for the future land-use characteristics. The -post-development conditions consisted of residential development, landscaped or undeveloped areas, commercial development, and impervious areas, consisting of surfaced roads and other building uses. The proposed development results in changes to the existing catchment areas. The land use between the different sub-catchment areas is dominated by residential areas in urban spaces and urban-rural development. The areas have high densification, which may increase surface run-off. The different land-use percentages were shown to consist of lawn and street land-use for consideration into the stormwater simulation for post-development conditions. The general slope of the site for post-development conditions is 2.5%, of which the area is predominately developed, resulting in high surface run-off and volume.

Base Scenario Mapping

The base scenario mapping consisted of the daily rainfall received from the TR102 for the Hennopsriver rain station. Although this daily rainfall is average, we considered it to understand its impact on the run-off results for the study area. The simulation was conducted using the selected design program. The model was run on Autocad Civil 3D for 24 hours to match the design storm durations. The total inflow volume is for the full mode 24-hour duration. The peak flows for the base scenario are also indicated in Table 2.

Scenario 1

The results show that a combined discharge of 917.79 m^3/s and 1 082.62 m^3/s for pre- and post-development conditions, respectively, can be expected for the overall study area. Prior to the zoning conditions being imposed on the study area, the pre-development conditions consisted of a fairly natural

TABLE 2: Results of Storm and Sanitary Analysis model on Civil 3D for Base Scenario Mapping, Scenario 1 and Scenario 2

Recurrence Internal	1 in 25 year	1 in 50 year	1 in 25 year	**1 in 50 year**	**1 in 25 year**	**1 in 50 year**
Peak flow at Outfall (m^3/s)	917.79	1 082.62	994.37	1 172.95	1 262.25	1 488.94
Total inflow volume (m^3)	3 263 210	3 442 077	3 535 495	3 729 286	4 487 953	4 733 952

landscape which encouraged stormwater infiltration. The introduction of post-development conditions yielded an 18% increase in stormwater run-off volume for the study area. Climate change impacts may exacerbate the stormwater impact resulting from the post-development conditions. The results shown of the Autocad Civil 3D modelling are summarised. The model was run for 24 hours to match the design storm durations. Scenario 1's amount of peak run-off for the entire area is summarised in Table 2. The results show that a combined discharge of 994.37 m^3/s and 1 172.95 m^3/s for pre- and post-development conditions, respectively, can be expected for the overall study area. The introduction of post-development conditions yielded an 18% increase in stormwater run-off volume for the study area. Climate change impacts may exacerbate the stormwater impact resulting from the post-development conditions.

Scenario 2

The existing and proposed post-development conditions for the model were kept consistent throughout the scenario analysis. Scenario 2 consisted of the daily rainfall analysed from the frequency analysis for the Pelindaba rain station and forecasted. As above, the simulation was conducted using the Civil 3D Storm and Sanitary Analysis. As provided in Chapter 3, the peak discharge for our proposed scenario 2 with the daily rainfall retrieved from the frequency analysis and subsequently forecasted for the 2020 to 2069 period. The results shown of the Civil 3D modelling are summarised. The model was run for 24 hours to match the design storm durations. The total inflow volume is for the full mode 24-hour duration, also shown in Table 2.

From the results, we can see that more frequent and intense rainfall is projected for the region, and the development of an area can affect the overall drainage of the area. Stormwater run-off can wash away sediments, important nutrients or any other pollutants into the natural watercourse, which may have adverse effects on the overall natural water cycle and other systems such as the environment and ecosystems. From the analysis, it is evident that climate change impacted rainfall and predicted rainfall could have an impact on the current development conditions of any region. Each of the hydrographs for the different scenarios peaked higher and faster than in pre-development conditions, which indicate that both the run-off volume and peak discharge are substantially increased under the developed conditions. Therefore, based on previous trends, there is a likelihood that the hypothetical area analysed in this dissertation will be under-designed over the next 50-year period should the climate impacts not be incorporated. This implies that the magnitude of these flood events will increase.

For the Roodekrans area, which was analysed with hypothetical land-use requirements, this will translate to an increase in precipitation in the area that may be subjected to flooding due to under-design. The stormwater run-off showed that we could expect an average increase of 26% over the study area between 2020 and 2069. From the assumption made on post-development conditions for this study and with the input information obtained from the design rainfall program, a peak flow value for this area could be determined for the 1 in 50- and 1 in 100-year extreme events, respectively, which takes into account the climate change impacts. This will allow for the accurate size determination of major stormwater infrastructure to facilitate the drainage of this volume of water from the study area.

CONCLUSION

The data received for this report indicated that over the area, there had been a substantial increase in rainfall events between 1969 to 1995 and 1995 to 2019. The percentage increase was the largest for most of the extreme rainfall events. The frequency analysis conducted for this study indicated that a 21% increase should be expected between the 2020 and 2069 period, with the intensity of a 2-year return period expected to increase by a staggering 40%. In light of this, the impact of climate change is evident, and thus stormwater management within this study area requires extensive thought process for future urban development. The rainfall and discharge for the base scenario were used to calibrate the model parameters of the catchment. The study area was divided into different sub-catchment with different catchment characteristics for post-development (urban development). These sub-catchments were established for the three (3) different scenarios. To analyse the impact, the stormwater run-off was analysed for the different scenarios. From the results, we could see how the different scenarios reacted to the increase in rainfall. Thus, to maintain the base scenario stormwater run-off, with the forecasted rainfall intensity, the areas were reduced to ensure that the developments do not become vulnerable to the risks of climate change.

From the analysis, it is very clear that the amount of greenfield area available for stormwater management should be identified early in project planning. This will largely dictate the extent to which different stormwater design elements are feasible in any development to ensure that climate change impacts are considered.

RECOMMENDATIONS

The rainfall data limitations, particularly the lack of rainfall data for longer periods, present challenges for planners and engineer. Although there are methods for replacing the data, an accurate representation of the required data would have ensured the homogeneity of the results is maintained. Considering the above, there is a need for a project funded by the government, which undertakes maintenance and backup rain gauges to be implemented across the country. This will be useful in providing the first approximation for a hydrological modeller or any practitioner to estimate peak discharges with accurate rainfall data.

The literature review shows that there is very little consideration for stormwater analysis during the feasibility and zoning stages of Greenfields. The increase in development poses a major risk for areas that may already be prone to flooding. Further consideration by the government to incorporate planners and engineer's recommendation in the planning of zoning of areas will ensure that the issues such as climate change are considered from the beginning.

An integrated approach needs to be adopted to determine the extent of encroachment of new development. Depending on the specific area, decisions can be made whether to allow no development at all or whether to allow some development with special conditions. For proactive planning of developments, impacts of climate change on stormwater management for the greenfield areas should be pre-defined.

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