# Evaluation of co-axial diagram for Namibian flood determination methods


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Flood determination in Namibia, with its variable climate, erratic drought and flood events and poor hydrometric data coverage, must frequently refer to empirical and deterministic methods. For the deterministic methods, three co-axial diagrams are used, which were originally developed in 1979 and which have not since been updated. The purpose of this study was to investigate the accuracy of one of the co-axial diagrams, namely the depth-duration-frequency (DDF) diagram, by using the latest available daily rainfall and following a similar methodology to that of the original publication. For most of the stations, the derived return levels of the individual stations were lower than the levels indicated in the 1979 co-axial diagram, indicating that the co-axial diagram is conservative, especially for higher return periods. The results highlight that the Namibian flood determination methods, with few exceptions, are in urgent need of updating and the derivation of new methods or approaches may even be warranted.


## 1. Background

Namibia's variable climate and lack of good quality, long-term hydrometric data often limits flood designs to the use of deterministic and empirical flood determination methods. All deterministic methods recommended by the latest edition of the Namibian Drainage Manual require the derivation of a design rainfall to determine the design runoff value (Roads Authority, 2014).

The determination of the design rainfall is dependent on the catchment area size and the location of the catchment area. Catchment areas are divided into 3 categories by size: small being less than 15 km$^2$, medium areas being between 15 and 5 000 km$^2$ and large being greater than 5 000 km$^2$. The catchment location is also divided into three categories, namely the Coastal, Northern and Southern regions. Determining the design rainfall for small areas requires the use of the co-axial diagram referred to as the depth-duration-frequency (DDF) diagram (refer to **Figure 1**), while doing so for large areas requires the use of a depth-area-duration-frequency diagram for the Northern and Southern Regions, while Coastal Regions are to use the DDF diagram for smaller catchment areas, regardless of the catchment area size. Medium sized catchment areas require a weighted combination of the small and large catchment area design rainfall approaches (Roads Authority, 2014). Most catchment areas will fall in the medium category and will therefore make use of the DDF diagram (though in weighted form) along with smaller catchment areas (Roads Authority, 2014). The DDF diagram as published in the Namibian Drainage Manual (2014) will be the focus of this article.

### 1.1 General Background to the Co-Axial DDF Diagram

Flood determination methods for both Namibia and South Africa were generally developed and published by the South African Department of Water Affairs in the 1970s and 1980s and were then adopted in design guidelines by road and transportation authorities. After independence from South Africa in 1990, the Namibian Department of Transport published their own Drainage Manual in 1993, which was largely a localisation of the South African Drainage Manual. The Drainage Manual was updated in 2014 and published by the Roads Authority of Namibia, remaining largely dependent on the South African equivalent. Flood determination methods published in the Drainage Manual of 2014 remained largely unchanged from the 1993 publication, with the methods mostly receiving a visual update to the relevant graphs used (Department of Transport 1993; SANRAL 2013; Roads Authority 2014).

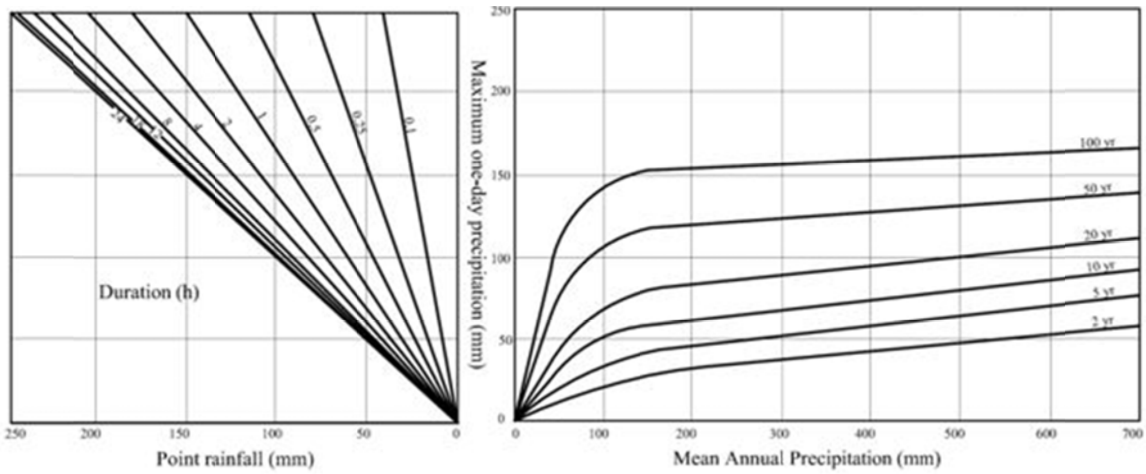


*Fig. 1. Co-axial Depth Duration Frequency Diagram (for ≤24 hour storm events)*

The recommended deterministic methods for flood determination in the Drainage Manual all require design rainfall determination and will mostly make use of the co-axial DDF diagram (refer to the discussion in the introduction and **Figure 1**). The co-axial DDF diagram was originally published in Report No. 3/79 of the Hydrological Research Unit (HRU) in 1979, as there were at the time no methods available to determine design rainfall in arid areas like Namibia (Richardson and Midgley, 1979). The only update to the method occurred in 1981, per HRU Report No. 14/81, with only additional diagrams added for longer duration storms.

The DDF diagram was derived from daily rainfall data to generate a maximum one-day precipitation per desired return period using Mean Annual Precipitation (MAP) as input. Fundamentally, the relationship between maximum one-day precipitation and MAP undergirds the entire diagram. For the development of the diagram, over 572 stations in Namibia where rainfall was recorded daily were considered, with 362 stations (63%) with record lengths longer than 20 years, 198 (35%) with record lengths exceeding 30 years and 45 stations (8%) with record lengths longer than 50 years. Data from stations with record lengths longer than 10 years were used for the derivation of the diagram.

From each station, the following was abstracted:

1. The annual maximum daily rainfall total per over the record;
2. The MAP for each station;
3. The mean and standard deviation of the natural log of the maximum daily rainfall record.

The MAP per station was then plotted against the two corresponding statistical parameters, namely the log-mean and log-standard deviation (also per station). Curves were then fitted through these relationships to generate equations for each of the two parameters with the MAP as the input variable. Log-mean and log-standard deviation values could therefore be determined over a range of MAP values. Each of these generated parameters were used as input into the log-Gumbel distribution to generate return levels for established return periods (2, 5, 10, 20, 50, 100 years) over the MAP ranges. Finally, curves were fitted through the return levels with mutual return periods over the range of MAP values, resulting in the curves seen in **Figure 1**.

The log-Gumbel distribution as described in HRU 3/79 is as follows:

$$F(x)=e^{-a+cy} \quad (1)$$

Where:

$c = \sqrt{6}.\sigma/\pi$
$a = \gamma c-\mu$
$\sigma$ = standard deviation
$\mu$ = mean
$\gamma$ = 0.57721 (Euler's constant)

Since its publication nearly 40 years ago, this diagram has remained unchanged. With longer and additional rainfall records available, it is only reasonable to re-assess the accuracy of this diagram.

## 2. Methodology

The purpose of this analysis is to assess if the DDF diagram (specifically the top right diagram used for maximum one-day precipitation) represents more recent maximum daily rainfall statistics. The premise of this analysis is that design rainfall derived from rainfall station(s) either within a catchment area or close to it would be more desirable than generalised relationships such as the DDF diagram. Stated differently: how would maximum one-day precipitation values derived from individual stations compare to the generalised DDF diagram?

It must be stated clearly that this analysis does not attempt to update the existing DDF curves in Namibia, but rather evaluate of the accuracy of the diagram using current rainfall data. This study was originally conducted as a final year civil engineering project for Mr Solver Sinombe at the Namibia University of Science and Technology in 2017.

### 2.1 Data acquisition

Historic daily rainfall station data was requested from the Namibia Meteorological Services (NMS), who have the largest and longest rainfall database in Namibia. The desire was to obtain all daily rainfall station data available, specifically for stations with record lengths exceeding 30 years. Obtaining the necessary data proved to be challenging, as the NMS was reluctant to provide complete station records for this study and provided different datasets containing different station data on different occasions, with different record lengths. The final dataset used for this analysis contained rainfall data of 217 stations across Namibia, whose record length was restricted to a maximum of 50 years by the NMS. However, it is considered highly unlikely that all stations with a maximum of 50 years data was submitted by the NMS, as data for known prominent and historic stations were not included. The analysed stations therefore do not represent the complete daily rainfall dataset available in Namibia.

### 2.2 Data processing

The selection of stations for further analysis was based on the following criteria. All stations that had a record length of less than 10 years were discarded from analysis. Secondly, if the record length of the individual station was more than 10 years but more than 15% of the record length was missing, that station was discarded. Similar to the approach followed for HRU Report No. 3/79, if critical rainfall data was missing, i.e. if the months between October through March during a particular year had little or no record, the entire year or that station was discarded.

Using these criteria, only 64 stations were considered for further analysis, shown in **Figure 2**. Of these stations, 18 stations had usable record lengths of 20 to 30 years, 19 stations with record lengths of 30 to 40 years and 27 stations with record lengths exceeding 40 years. Unfortunately, due to the seemingly odd selection criteria used by the NMS for the provision of data and the selection criteria applied for this analysis, no stations located in the centre- to north and north east of Namibia were included in the analyses. Only data from stations located in the central and southern regions of Namibia could be analysed.

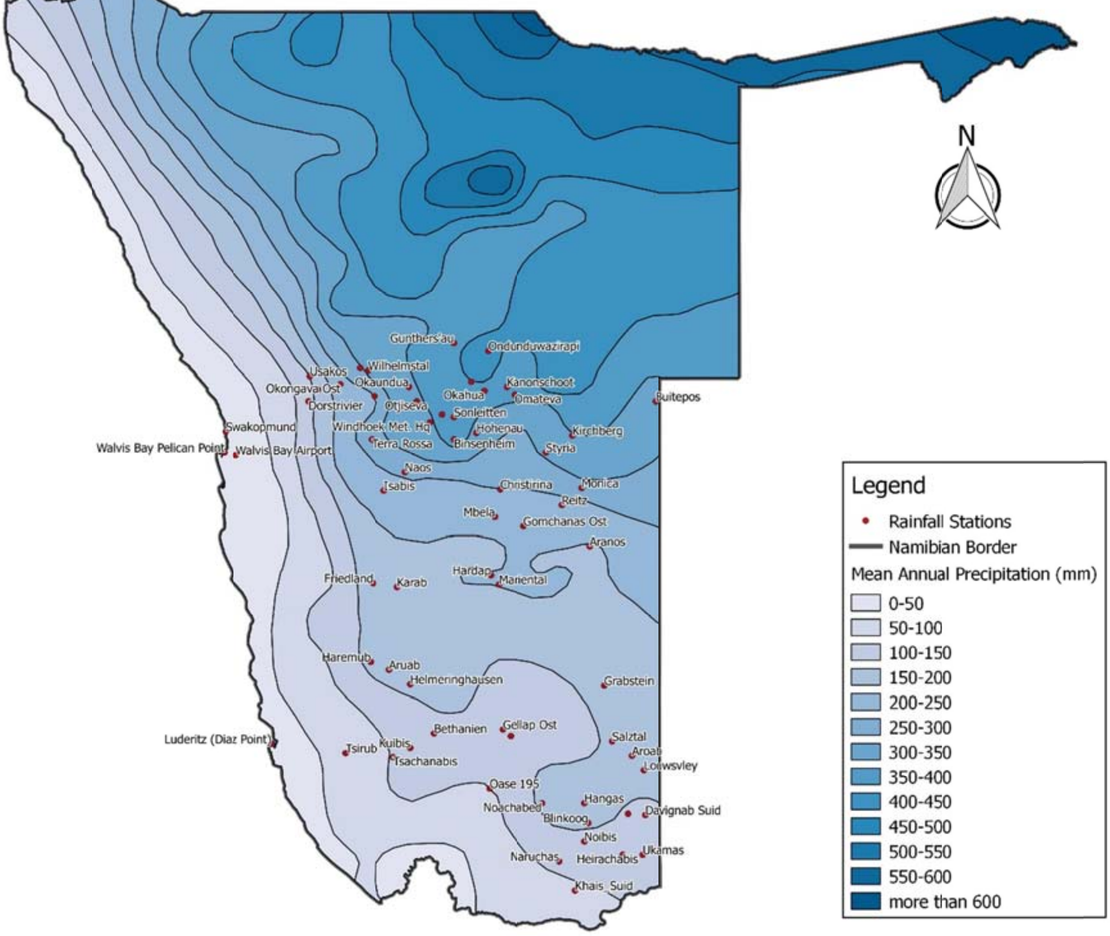


*Fig. 2. 64 Rainfall Stations Selected for Analysis*

**2.3 Data analysis**

Data analysis was done on a simplified basis, applying a similar methodology to that followed with the preparation of the HRU Report No. 3/79, whereby of the stations considered for analysis, annual maximum daily rainfall values were recorded, MAP values were generated per analysed station and return levels were derived for each station based on the log-Gumbel distribution (see Equation 1). These individual return levels per station were then plotted over the original DDF diagram as shown in shown in **Figure 3** for selected return periods. The solid lines represent the original DDF curves for selected return periods, while the points represent corresponding derived return levels of individual stations.

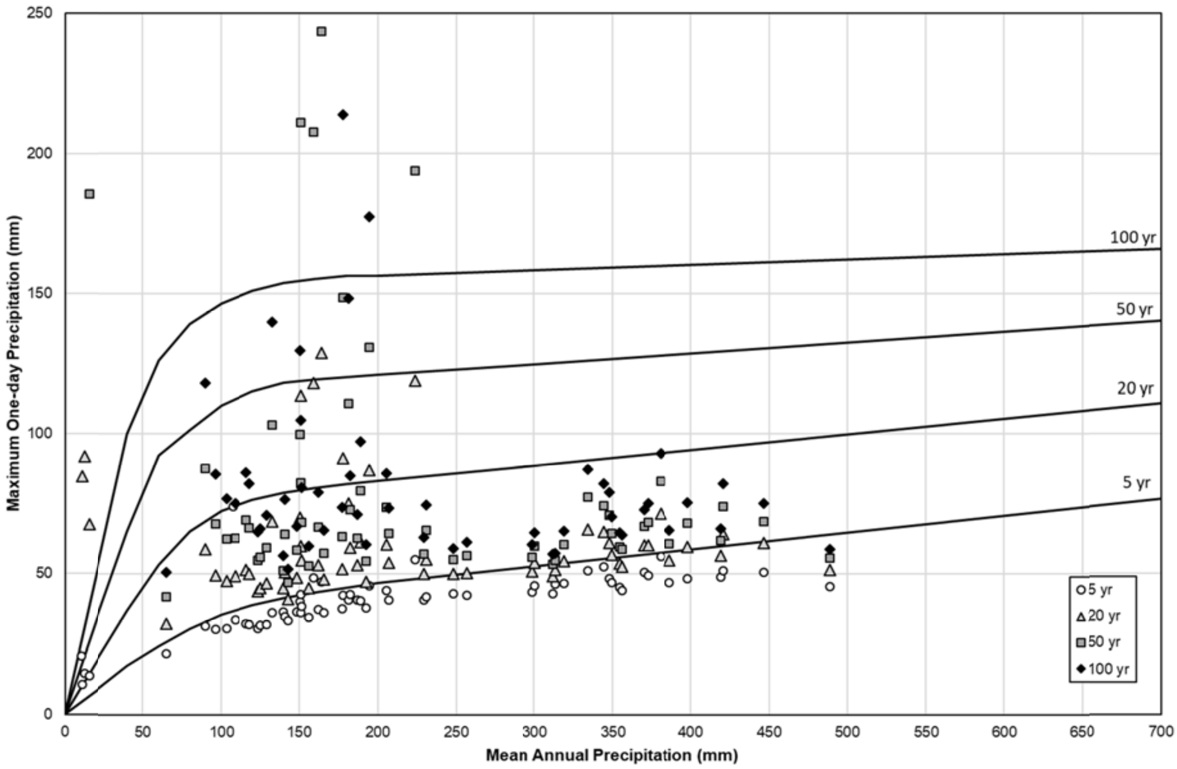


*Fig. 3. Return Levels for Individual Stations Analysed compared to DDF Diagram*

Two clusters of points can be observed, one for MAP values between 100 and approximately 250 mm, and the second cluster between approximately 300 and 500 mm. As the MAP increases, so the cluster of points tend to converge around a smaller area. Return levels in the 0-50 mm MAP range were very high and were omitted from **Figure 3**. These mostly represent coastal regions where the maximum daily rainfall very often exceeds the MAP. Consequently, high standard deviations in the data can be expected, resulting in extreme return levels. For example, the analysis for Walvis Bay: Pelican Point, with a 28 year record and MAP of 10 mm, generated a 100 year return level of 5 861 mm, which is completely unrealistic.

Most return levels plotted are below the corresponding DDF diagram values per return period, specifically for MAP values exceeding 100 mm. Return levels of some stations were higher than the DDF return levels, though these typically occurred for stations with a MAP lower than 200 mm. For a return period of 2 years, 72% of all stations and 93% of stations with a MAP > 200 mm showed return levels higher than the corresponding DDF return level. The near inverse occurs for return periods above 2 years, with 83-86% of all stations and 96% of stations with a MAP > 200 mm having return levels higher than the corresponding DDF return levels. **Table 1** provides a summary of the percentage difference between the DDF curves and the analysed station return levels over a range of MAP values. Negative values indicate lower return levels than the corresponding DDF return levels, while positive values indicate higher return levels than the corresponding DDF return levels.

*Table. 3. Percentage difference between return levels of individual stations and DDF diagram*

| **Relevant Stations** | **Return Period (years)** | | | | | |
|---|---|---|---|---|---|---|
| | **2** | **5** | **10** | **20** | **50** | **100** |
| MAP > 150mm | 4% | -12% | -20% | -26% | -32% | -33% |
| MAP > 200mm | 8% | -14% | -25% | -34% | -45% | -51% |
| MAP > 300mm | 8% | -15% | -27% | -37% | -49% | -55% |

As the MAP increases, so the difference between the individual station's return level and corresponding DDF return levels increase, especially for higher return periods. The exception to this occurs with stations with MAP values lower than 100 mm, which typically have return levels that exceed the DDF curves, the reasons for which are discussed above.

Overall, return levels derived from individual stations are in most cases lower than those of the DDF curves, and become considerably lower as the return period increases.

## 3. Discussion

Due to the limited scope of this analysis, further investigations must be conducted to determine why the rainfall data used for this analysis generally produced return levels lower than the available DDF curves and if similar results are observed with a more complete and representative rainfall dataset, since only stations in the central to southern regions of Namibia were analysed.

As shown in **Figure 3**, return levels generated for many individual stations did not even exceed the corresponding DDF values for a 20 year return period. This is true for all stations with a MAP > 300 mm. The implication here is that if the DDF diagram is used for a 20 year design rainfall, it would generate a design storm which exceeds return levels generated from individual rainfall stations as high as 100 year return periods. This indicates that the DDF curves are extremely conservative when compared to the analysed rainfall data. This will consequently result in the possible overestimation of design rainfall and consequent overdesign of related infrastructure (culverts, bridges, etc.). This was also acknowledged to a certain extent in HRU Report No. 3/79, which mentions that 20% of the maximum daily rainfall values for all stations were below the 20-year line, 74% were below the 50-year line and 93% were below the 100-year line of the DDF diagram. Interestingly, 45%, 84% and 95% of the maximum daily rainfall values from this analysis were below the 20-, 50- and 100-year lines respectively.

It must emphasised that this analysis does not represent an update of the method, but rather an initial and simplified assessment of the accuracy of the 1979 DDF diagram. The exact methodology detailed in Report No. HRU 3/79 was not followed, specifically regarding the relationships between MAP and the log-mean and log-standard deviation of all the analysed data. The establishment of these relationships in HRU Report No. 3/79 involved multiple attempts at curve fittings, especially regarding the MAP – log-standard deviation relationship, which is the most sensitive parameter in the log-Gumbel distribution. It is posited that the MAP – log-standard deviation relationship is the most likely explanation for the difference between the original DDF curves and the analysed data. However, this must be confirmed with further assessments.

An additional factor to be investigated is the assumed relationship between MAP and maximum daily rainfall. This assumption is key to the derivation of the DDF diagram: Maximum one-day precipitation increases as the MAP increases. Whilst this may seem intuitive, it does not necessarily follow that higher mean annual rainfall corresponds with higher daily storm events. For example, it is possible that large storm events, including large daily rainfall totals, occur in unremarkable rainfall years (low MAP). These factors must be investigated and re-established, especially in the Namibian context with its highly variable rainfall conditions and tendency towards extremes. Confirming this assumption was unfortunately beyond the scope of this study.

Ultimately, this study was aimed at assessing how the DDF curves, derived nearly 40 years ago, compare to current available rainfall data, in this case for the central and southern regions of Namibia. It was shown that there is reason to question the validity of the DDF curves as these seem overly-conservative from a design point of view. If anything, this study highlights that urgent reviews and updates of the Namibian flood determination methods and specifically the DDF diagram, are required.

## 4. Recommendations

The analysis was greatly limited by the data provision by the Namibia Meteorological Services, who struggled to process the data requests for this analysis and submitted a limited dataset that ended up only reflecting stations located in the centre to south of Namibia. Discussions around the value of data must be had with data providers, in this case the NMS, so that uncertainties and misunderstandings can be clarified. Data providers must also be more transparent with the data they have available, in order to assist the analyst with the better processing of data requests.

This may include providing geographic coordinates of the stations; indicating what record length is available and how many errors and missing data readings the dataset contains.

Further investigations into the validity of the DDF diagram and much needed updates are highly recommended. These investigations must include a more representative and complete dataset. Furthermore, the methodology of HRU Report No. 3/79 should be followed to produce new (updated) curves. Other extreme value distributions can also be incorporated in lieu of using only the log-Gumbel distribution. Even more critically, the relationship between MAP and maximum daily rainfall must be re-established for the DDF diagram to still be valid, otherwise other methods for generating design rainfall should be considered. For example, factors such as regional climatic zones and / or rainfall characteristics could be considered for the estimation of design rainfall.

Namibia is indebted to the contribution of the hydrologists of the 1970s and 80s whose methods are still in use to this day, a generation later. Whilst their methods have proven to be enduring, it can certainly be agreed that they themselves would have recommended periodic updates and reviews into the methodology, as new information and more data became available. We hope this study will spark renewed interest and investigations into Namibian design flood methodologies.

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