Integrating climate change information into long term planning and design for critical water related infrastructure in Windhoek and other African cities.

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Abstract

The planning horizon for water infrastructure such as bulk water supply, dams, stormwater and hydraulic structures is typically 25-100 years. It is therefore critical that climate change information is incorporated into the planning and design of these important urban assets. This is particularly relevant for cities in Africa which have a backlog in critical water infrastructure and are experiencing significant growth that in many cases is exceeding the capacity of existing infrastructure. This paper discusses the current practice of assimilating climate information in the infrastructure design process for water related infrastructure describing current design standards and typically used datasets. The city of Windhoek in Namibia is used as a case study to demonstrate how the process of co-exploration of climate change risks can result in research that will be of use to decision makers. This study outlines appropriate parameters and temporal and spatial scales necessary to support the integration of climate change into long term infrastructure planning and design that is applicable to all cites. An example is presented of potential changes in extreme rainfall at the local level to illustrate consequences of not updating design standards with future climate change information.

1. Introduction

The population and spatial extent of southern African cities are increasing at an increasing rate. This has placed the local governments of these cities under pressure to provide services for the ever growing population who predominantly live in informal settlements (Tyler and Moench, 2012). In addition, environmental concerns have changed and are broader in scope with some at a global scale, such as climate change. This has produced associated changes in policies and with that regulations and standards. Houghton (1998, 114) notes that standards give off the “aura of science, its objectivity and apparent solidity” and are “used in practice ‘as if’ they are permanent and immutable” (Ponte, 2013, 464).

In an engineering context, in everyday practice in relation to flooding and drainage design:

“the majority of routine (low-cost) studies use naïve and outdated formulas or models, applying them as “recipes”. Indeed, most of the widely employed semi empirical approaches for estimating flood design “loads” were developed many decades ago, yet have been only occasionally validated, updated and adapted to local conditions” (Efstratiadis et al., 2014, 1417).

The planning and design of new water infrastructure in African cities needs to consider a number of variables such as the increase in demand for water from both formally planned and informal settlement, rapid land-use change and a highly variable climate. Added to this are the increasing temperatures and possible modification to precipitation patterns caused by climate change. The urban water infrastructure needs to be resilient to these wide range of shocks and stressors (Leichenko, 2014). The planning horizon for water infrastructure such as bulk water supply, dams, stormwater and hydraulic structures is typically 25-100 years. Design standards for water infrastructure and water resources planning are based on historic climate information. An important assumption for these standards is the statistical stationarity of precipitation extremes i.e. the statistical properties, such as the mean, remain constant (Rosenberg et al., 2010). This assumption may not be applicable under future climate conditions due to changes in rainfall intensity, duration and frequency.

In light of the above challenges, the Future Resilience for African Cities and Lands (FRACTAL) project aims to enhance knowledge on how to integrate regional climate responses to global change into decision making at the city-region scale in southern African cities (Fractal.uct.ac.za). The specific objective of FRACTAL is to adopt bottom-up, co-exploration and co-discover approach to identifying critical climate risks and targeting climate change research on key issues relevant to design makers. FRACTAL is focused on three tier one cities in Africa including Windhoek, Lusaka and Mozambique, as well as three tier two cities (Blantyre, Gaborone and Harare) and three additional self-funding cities (Cape Town, Durban and Johannesburg). This study is focused on the key issues from the City of Windhoek.

This paper aims to identify crucial climate information needed to support decision making and demonstrate the benefits of co-exploration and collaborative design in identifying the critical issues and information requirements for sustainable infrastructure decision making. The paper situates the issue of engineering design standards for water infrastructure in a governance context and within the social learning context of the collaborative learning lab process inherent in FRACTAL, and it falls within the Nexus cluster of the project and involves engineers, natural and social scientists and hence uses quantitative and qualitative methods (mixed methods) of analysis.

Since this paper focusses on engineering design standards for critical urban water infrastructure, it is important to understand the role of standards in infrastructural development. Standards can be viewed as a ‘technology of regulation’ (Gibbon and Hendriksen, 2014) and hence they fall more broadly within a governance framework (Kerwer, 2001; Ponte et al., 2011). Essentially, standards form part of regulation in society “to enforce socially desirable outcomes” (Ponte, 2013, 464). With the potential risks resulting from an increasingly variable and changing climate, it is critical to review the conventional design standards in order to reduce risk to both people and the environment, and shift the emphasis from ‘efficiency’ to the normative goal of risk reduction (Tissermans-Epstein, 2010).

It is therefore argued that design of water infrastructure standards is not politically neutral, as standards serve to determine the levels of acceptable risk in the management of water infrastructure. The collaborative learning lab processes in FRACTAL provide a forum in which this issue is being deliberated by scientists, engineers and local stakeholders (e.g. City of Windhoek) together. This lead to the identification of the critical risks addressed in this paper.

This paper discusses the current practice of assimilating climate information in the infrastructure design process, using Windhoek as a typical example, and describing design standards and typically used datasets. Subsequently, based on future climate projections it outlines appropriate parameters and temporal and spatial scales necessary to support the integration of climate change into long term infrastructure planning and design. A case study is presented of a typical flooding and drainage study used to design critical water infrastructure and for land use planning that demonstrates the consequences of not updating design standards with recent and future climate change information.

2. Methodology

The basic approach to the study is described below.

2.1 City Learning lab to identify critical climate change risks and burning issues

One of the ways co-exploration and collaborative design is implemented is through city based Learning Labs where the themes of resilience and climate change are discussed and the key issues are identified through co-participation and co-learning. The research focus of the project team is guided by the critical burning issues identified during the Windhoek Learning Lab and the research outcomes are then presented at the next Leaning Lab (Figure 1).

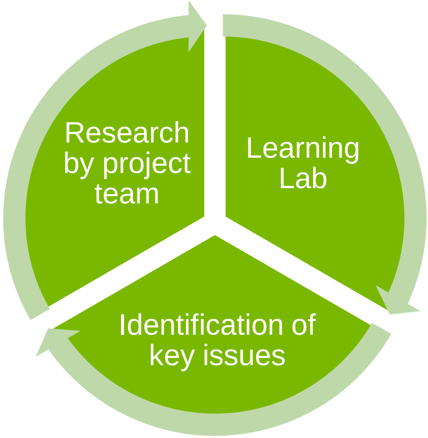

Figure 1: The iterative co-learning process

2.2 Review of Engineering Design Standards for Water Infrastructure:

The relevant water legislation and policy documents, for Namibia and Windhoek were sourced, as well as the regulated standards and guidelines for the design of key water infrastructure including water supply, flooding and drainage, and dam safety. Additional discussion were held with key city officials, engineers and other professionals involved in the design of critical water infrastructure to identify best practice design standards and current approaches to integrating current climate and future climate change information into the design process.

2.3 Case study example

The research adopts a case study approach, which serves to demonstrate the application of design standards within the context of Windhoek.

3. Results

3.1. Windhoek City Learning Lab

The first Windhoek Learning Lab took place in March 2017 and the participants comprised of representatives from the City of Windhoek, NamWater, national government, climate and energy related NGOs, Shack Dwellers Federation, academics, consulting engineers and climate organisations. The burning issues related to water were identified through this group, and stimulated the research process undertaken for this paper by the project team.

One of the burning issues identified related to water was “What climate information is needed to support the development of climate resilient water infrastructure for Windhoek?” The paper is a response to this expressed need of the participants, particularly those from officials from the City of Windhoek, NamWater and the national Ministry of Agriculture, Water and Forestry. Water infrastructure is a broad term and we have subdivided it into three categories: Water Resources Planning, Stormwater Management and Flood Management.

3.2. Water Infrastructure Planning and Design Framework

Design standards provide engineers with guidance and are based on experimental studies and practical experience and represent safe practice. For a standard to be implemented it has to be accepted by project initiators and the engineering community. The water governance institution stipulates design standards to be within the regulatory framework in order to mitigate risk (Aisz and Burell, 2006). A framework showing the linkages between water institutions, design standards and the engineering community in the design and planning of water infrastructure are represented in Figure 2. The lighter grey links in Figure 2 illustrate the weaker association between climate scientists and the engineering community and design standards used in infrastructure planning. The Learning Lab approach taken in FRACTAL is one way of strengthening this association.

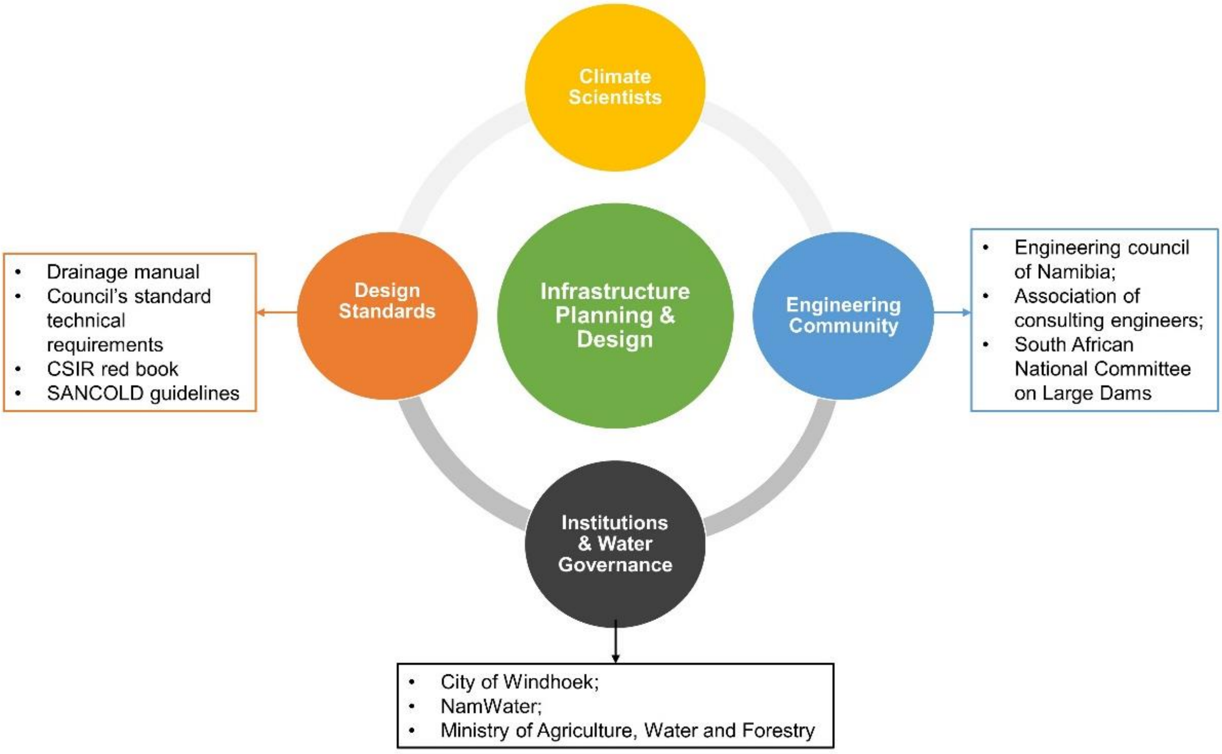

Figure 2: Infrastructure planning and design framework

3.3. Water Governance

The water governance in Windhoek, like other cities, involves the interactions of different state institutions (Figure 2). The Ministry of Agriculture, Water and Forestry's mandate is to promote, develop, manage and utilize natural resources for sustainable and equitable development and it is tasked with the long term planning of water resources. The Namibia Water Corporation Ltd (NamWater) is a state owned enterprise tasked with supplying bulk water to municipalities and industries. The City of Windhoek is responsible for the supply, distribution and quality of potable water, and it stipulates guidelines for use in stormwater design and management.

3.4. Water Infrastructure Planning

3.4.1. Water resources planning

The City of Windhoek is considered a leader in the continent in water demand management, water re-use and water efficiency (Still et al., 2008). In terms of water resource modelling the Namibian approach has been the same as the established method in South Africa. The standard modelling tools in water resources planning are the conventional Pitman Rainfall Runoff Model and Water Resources Yield Model.

The Pitman Model is a lumped rainfall-runoff catchment model which simulates the movement of water through an interlinked set of modules, each of which represents a physical component of a catchment i.e. catchments, river reaches, reservoirs, irrigation areas and mines. It is operated on a monthly time step it requires a times series of monthly rainfall and mean monthly evaporation. For the purposes of water resources planning the Pitman Model is used to generate naturalised flow records, which are flows records without water abstractions, for use in the Water Resources Yield Model.

The Water Resources Yield model is a monthly stochastic yield reliability model used to determine the water supply system yield capability at present day development levels. The model allows for scenario-based historical firm and stochastic long-term yield reliability analysis. In addition, short term reservoir yield reliability can be determined, given current starting conditions (Seago, 2016).

3.4.2. Dam water quality modelling

Reservoir water quality modelling is an important component of water allocation plans and water quality management plans. A combination of hydrodynamic models and water quality models are used to model reservoir water quality processes and stratification in southern Africa (DWAF, 2003). The climate information required includes rainfall, temperature and wind speed. The temporal scale can vary from daily to monthly depending on the purpose of the modelling.

3.4.3. Stormwater

Stormwater infrastructure is used to effectively manage stormwater quantity (flow and volume) as well as quality. The infrastructure is designed to manage runoff to an acceptable level of risk for a range of annual exceedance probabilities (chance of being exceeded in any given year), typically:

- Pipe network 1:2 year to 1:10 year recurrence interval (0.5 to 0.1 annual exceedance probability);
- Roads and regional stormwater structures such as canals are designed to 1:50 year to 1:100 year recurrence interval (0.02 to 0.01 annual exceedance probability).

The design standards of hydraulic infrastructure are based on rainfall intensity-duration-frequency (IDF) curves which are derived from sub-daily rainfall i.e. hourly rainfall. An assumption in generating intensity-duration-frequency curves is that precipitation patterns and distributions are spatially similar within the catchment and will remain statistically stationary through the lifetime of the infrastructure (Tfwala et al., 2017). The guidelines for stormwater in the City of Windhoek include the Council's standard technical requirements (City of Windhoek, 2013), the Namibian Drainage Manual (Department of Transport, 1993) the South African Council for Scientific Research (CSIR) red book (CSIR, 2005).

3.4.4. Fluvial flooding

The floodline determination involves a detailed hydrological (design flood) analysis, and a detailed hydraulic (floodline) analysis to determine the extent and impact of the design flood. The rainfall information and methods contained in the Namibian Road Drainage Manual (1993) are used to determine the design flood. For hydraulic modelling the U.S. Army Corps of Engineers (USACE) Hydrologic Engineering Centre River Analysis System (HEC-RAS) software (USACE, 2010) is widely used in southern Africa.

3.4.5. Dam safety

In the Namibian Water Resources Management Act (2004:41, 2013:65), powers are given to the Minister who may, at their discretion, appoint a suitably experienced professional engineer to determine the safety risk of a dam or to perform a safety evaluation on an existing dam. The evaluation shall be done in accordance with acceptable engineering practices. These 'practices', however, are not defined in the Act (Cullis et al., 2006). Extreme flood hydrology in Namibia has, for the past thirty years, largely been based on the South African Department of Water Affairs Technical Report 137 (TR 137) of 1988 (Cloete, 2015). The guidelines for dam safety by the South African Committee on Large Dams are also utilised.

4. Climate information requirements in water Infrastructure planning and design

The results of the review of the current use of standards for the engineering design of water infrastructure suggests that that the conventional and established standards are not adequate to cope with climate variability in the face of a changing climate. It is believed necessary to consider how standards could be interrogated and changed to deal with a changing climate, and how climate information could be included in water infrastructure design standards.

For the three components of water infrastructure that have been identified in this paper, the use of climate information is integral to the decision making process. Table 1 presents the integration of climate information into the three systems of water infrastructure planning and design show what climate information is required and at what spatial and temporal scale.

Table 1: Water infrastructure planning and design climate information requirements

System	**Function**	**Climate Information Required**	**Spatial scale**
Water Resources Planning	Catchment modelling Water supply systems modelling	Monthly time series of rainfall, temperature, evaporation and relative humidity.	Regional for multiple catchments. Inter-basin transfers
	Dam water quality modelling	Daily time series of rainfall, temperature, wind speed	Depending on purpose of modelling sub-daily through to monthly rainfall and temperature
Stormwater Management	Design of pipes, culverts & canals Water sensitive controls	Time series of daily annual maximum rainfall. Sub-daily rainfall intensities.	Site specific, sub-catchment city wide
Flood Management	Fluvial flood management Dam safety	Time series of daily annual maximum rainfall	Catchment

Figure 3 indicates the temporal and spatial scale of climate information as it related to the needs for design of water infrastructure. In general, as the spatial scale of the climate information required moves from the city level to multiple catchments covering thousands of square kilometres then the temporal scale of the climate information moves from sub-daily to monthly.

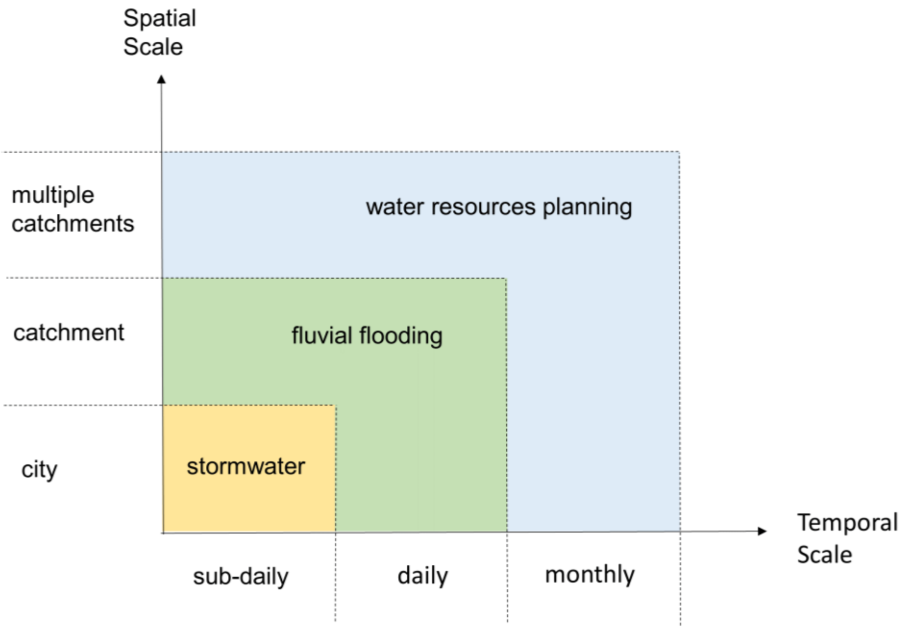

Figure 3: Temporal and spatial scale of climate information for water infrastructure planning and design

5. Case Study: Flood Study on the Upper Arebbusch Catchment

In order to illustrate the importance of incorporating climate change considerations into the decision making process for critical city water infrastructure, and typical flood study using a standard deterministic flood method (i.e. rainfall that is translated into a flood) was applied to the upper catchment of the ephemeral Arebbusch River which flows through Windhoek (Figure 4).

In this Study, the Regionalised Synthetic Unit Hydrograph method was used (HRU, 1972). The methodology was developed for southern Africa by the Hydrological Research Unit of the University of the Witwatersrand and presented in the well-established guide for design flood determination in South Africa (Smithers, 2012). The design rainfalls from the Namibian Drainage Manual (Department of Transport, 1993) were used to derive design flood peaks for the 1:50 year recurrence interval. Design rainfall is defined as the rainfall depth associated with a given annual exceedance probability and duration. The Hydrological Research Unit of the University of the Witwatersrand (HRU, 1972) developed synthetic Regionalised Unit Hydrographs in South Africa for distinct “veld zones”. These Veld Zones can broadly be interpreted as quasi-homogeneous, bio-climatic zones. Veld Zone 6 was used in this study which is applicable to arid and semi-arid climates in summer rainfall areas. The Unit Hydrograph is dimensionalised for each catchment in two steps: Firstly, the time axis (X-axis) values are multiplied by the Basin Lag. The Basin Lag is a function of the length of the longest watercourse, the average slope of that watercourse, the distance along that watercourse to the point nearest the catchment centroid and a Veld Zone coefficient (see Table 3 for Basin Lag value). Secondly, the discharge axis (Y-axis) values are multiplied by the unit hydrograph peak, which is a function of the catchment area, the basin Lag and a further Veld Zone coefficient.

For deterministic methods, such as the synthetic unit hydrograph, a crucial input is the design rainfall. Daily rainfall was obtained for from the World Climate Research Program (WCRP) Coordinated Regional Downscaling Experiment (CORDEX) (Giorgi et al., 2009). Analysis of the ensemble of Regional Climate Models within CORDEX show that the multi-model average generally outperforms any individual simulation (Pinto et al., 2015).

A probabilistic rainfall analysis was performed on a time series of mid-century annual maximum daily rainfall for nine Regional Climate Models for two Representative Concentration Pathways (4.5 and 8.5). Representative Concentration Pathway 4.5 is a scenario where greenhouse gas emissions peak mid-century and then decline, Representative Concentration Pathway 8.5 is a scenario where emissions continue to rise throughout the 21st century. Exceedance probability distributions were fitted to the daily annual maximum rainfall to determine values at various recurrence intervals for the mid-21st century. These values were compared against simulated historic rainfall to obtain a change for the extreme rainfall. A mean of the deltas obtained from the nine Regional Climate Models was then applied to the 1:50 year rainfall to obtain a design rainfall for Representative Concentration Pathways 4.5 and 8.5.

The upper Arebbusch River catchments characteristics are indicated in Table 2 and the resulting flood peaks obtained for the upper Arebbusch River catchment, for the current day and mid-century (2060) using the synthetic Unit Hydrograph are presented in Table 3 and Figure 5.

Table 2: Catchments characteristics of the upper Arebbusch River

Area	41.5 km^2
Longest watercourse	14.0 km
Average channel slope	0.016 m/m
Basin Lag	2.1 hours
Distance to centre of the catchment	8.2 km
Critical storm duration	4 hours

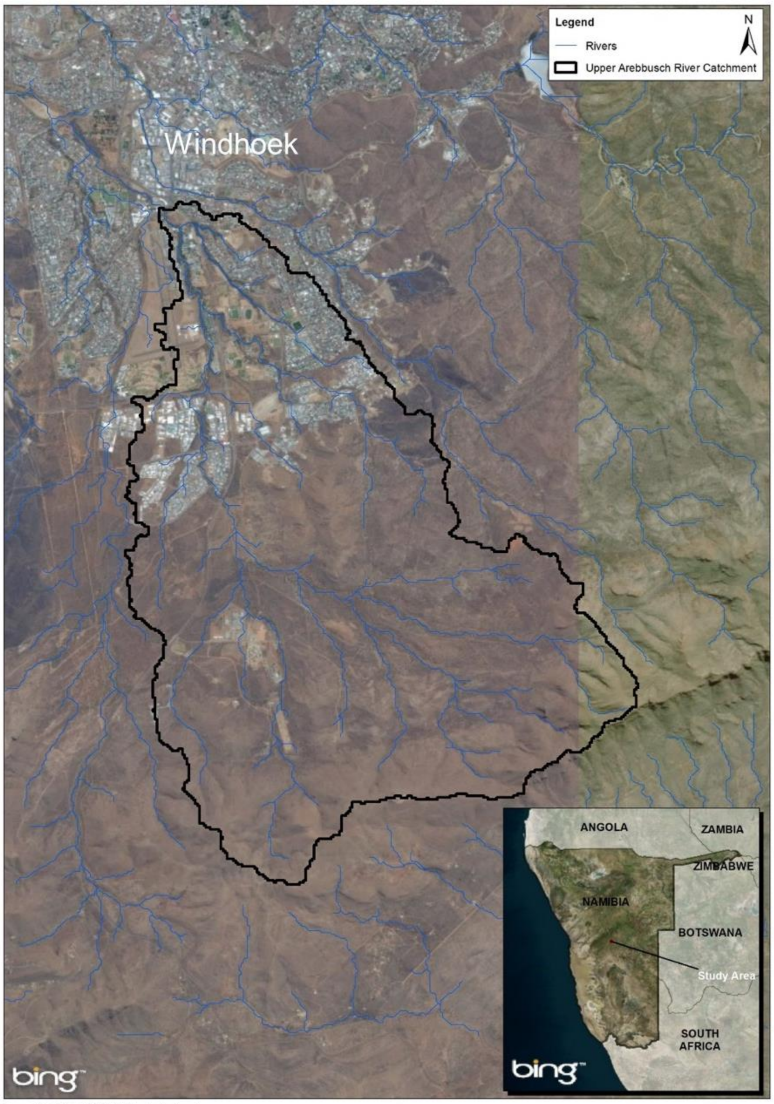

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Figure 4: Upper Arebbusch River catchment

Table 3: Results of flood peak analysis for the 1:50 year rainfall (0.02 annual exceedance probability) on the Upper Arrebusch River for mid-century (2060)

Scenario	1 in 50 year 1-day Design Rainfall (mm)	1: 50 year (0.02 annual exceedance probability) Flood Peak (m^3/s)
Current standard (Namibian Road Drainage Manual)	110	160
Representative Concentration Pathway 4.5	98	140
Representative Concentration Pathway 8.5	177	355

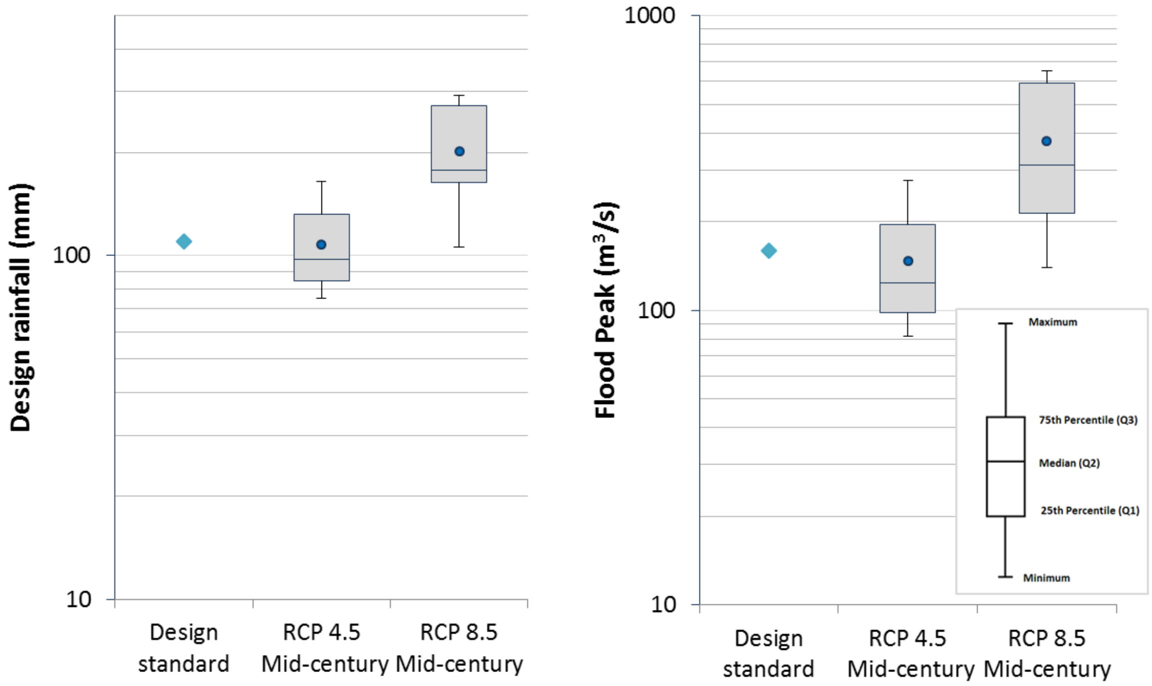

Figure 5: Box and whisker plots of design rainfall and flood peaks from nine climate models for the 1:50 year rainfall event in the upper Arebbusch catchment

6. Discussion

The potential changes to the flood peak for the 1:50 year flood (0.02 annual exceedance probability) show a show a range of impacts from an 11% decrease (RCP 4.5) to a 61% increase (RCP 8.5) for the two climate scenarios. The peaks given in Table 3 represent the mean change from nine Regional Climate Models. Figure 5 illustrates that increases in the design rainfall are magnified through the hydrological system and that a 50% increase in design rainfall results in an increased flood peak of 80% in the upper Arebbusch catchment. The increase in runoff for RCP 8.5 scenario potentially means an increase in the risk of flood damage from higher flow velocities in the river channel and flooding over a wider area. This has implications for existing infrastructure and for future planning decisions. The increased runoff for the RCP 8.5 scenario is due to a change in extreme rainfall only it does not account for land-use change in the catchment. Land-use change, both planned and unplanned, could also lead to increase runoff. As highlighted in Windhoek Learning Lab the increase in informal settlement in Windhoek has already seen people moving into the flood plains of ephemeral watercourses. More people will be affected by flooding if the magnitude of floods increases. An increase in the size of floods in the Arebbusch catchment could also have dam safety implications for Goreangab Dam situated downstream where the higher flood peaks could exceed the dam safety levels.

7. Conclusion

The paper provides a case study of the increase in potential risks for Windhoek, particularly in the informal settlements, resulting from an increasingly variable and changing climate. It demonstrates that it is critical to review the conventional design standards for critical water infrastructure to reduce risk in the face of climate change (Tissermans-Epstein, 2010).

We give a transparent and open demonstration of the calculations and data necessary for the development of climate change sensitive design standards which consider the potential increase of extreme rainfall events and can contribute to the recognition for the need for an interrogation of engineering design standards in order to reduce risk, decrease cost and adapt to climate change. Since standards are ‘recipes for reality’ (Busch, 2011; Ponte, 2013), climate sensitive standards will provide for a less risk-prone social and environmental future reality and a more resilient city.

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