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FACULTY OF FORESTRY AND WOOD SCIENCES

DEPARTMENT OF WATER RESOURCES AND ENVIRONMENTAL MODELLING

Changes in hydrological regime on Chongwe catchment – Zambia after land use changes in the 1980s

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DIPLOMA THESIS

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By

Moses Ngongo Chisola

MSc in Forestry, Water and Landscape Management

Supervisor: Ing. Michal Kuráž, PhD

CZECH UNIVERSITY OF LIFE SCIENCES PRAGUE

Department of Water Resources and Environmental Modeling

Faculty of Forestry and Wood Sciences

DIPLOMA THESIS ASSIGNMENT

Chisola Moses Ngongo

Thesis title

Changes in hydrological regime on Chongwe catchment - Zambia after land use changes in 1980s

Objectives of thesis

The aim of this thesis is investigate an influence of the land use changes that appeared in Zambia in 1980s on the water regime of Chongwe river.

Methodology

1. The available climatic limnigraphic data overlaps the period of the dramatic land use changes that appeared on Chongwe catchment in 1980s.
2. An analysis of the rainfall volumes and outflow volumes will provide an indicator of the land use effect on hydrological regime in this particular area.

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The proposed extent of the thesis
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land use, infiltration, rational method, runoff coefficient

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The Diploma Thesis Supervisor
Kuráž Michal, Ing., PhD.

Thesis Consultant
Ing. P. Máca, PhD.

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prof. Ing. Pavel Pech, CSc.
Head of the Department

Electronic apporoval: March 20. 2014

prof. Ing. Marek Turčáni, PhD.
Dean

DECLARATION

I hereby declare that I wrote this diploma thesis independently, under the direction of Ing. Michal Kuráž, PhD. I have listed all the literature and publications from which I acquired information. This thesis is hereby submitted for the Master of Science in Forestry, Water and Landscape Management at the Department of Water Resources and Environmental modelling at the Czech University of Life Sciences in Prague. To the best of my knowledge this thesis has not been submitted before for any degree or examination in any University.

Name:……………………………………………………………………………..………

Signed:……………………………….. day of ……..……………………………2014

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ABSTRACT

Three periods of forest management have been noted in Zambia: (i) a period of good forest management (before 1980), (ii) declining forest management (1980 to 1989) and (iii) poor forest management (1990 to date). In addition, increased Charcoal production, human settlement, urbanisation, and agriculture in recent years have all led to rampant deforestation and soil degradation in Chongwe catchment. However, the impacts of these land use changes on the flow regime of Chongwe are inadequately documented. This is despite the upstream vs downstream conflicts involving water use that have persisted since the 1990s in the catchment.

This study used time series analysis including; double mass curves, Runoff Coefficients (based on Rational method), mean monthly flows, and flow duration curves to analyse the changes that have occurred on the hydrologic regime after land use changes in Chongwe catchment. Based on double mass curve analysis (supplemented by the Petitti test), three windows (pre 1976, 1979-1989, 1990-2006) representing different levels of human impacts on streamflow were selected.

A decrease in rainfall of 14.7 % was observed when the baseline (pre 1976) is compared to the post impact period (1990-2006). Temperature on the other hand showed a 4 % increase in the same period. However, runoff at Ngwerere weir and Chongwe 5025 increased by about 36 % and 8 % respectively. This increase in runoff is unexpected because rainfall which is the only source of runoff in the area has decreased while temperature has increased. Moreover, runoff coefficients increased by about 40 % and 29 % at Ngwerere weir and Chongwe 5025 respectively; thus indicating increased runoff generation from less rainfall in the recent period (1990-2006). The results further indicate a one month shift in the time of peak flow at the urbanised tributary of Ngwerere from February to January. There is also an increase in peak flow amount at all stations and the reduction in dry season flows at Chongwe 5025. Land use change in the catchment can largely be held responsible for these results; mainly through reduced infiltration capacity and reduced water holding capacity of the soil.

Key words: Land use, infiltration, rational method, runoff coefficient

ACRONYMS

CDC	Chongwe District Council
CSO	Central Statistical Office
DWA	Department of Water Affairs
IUCN	International Union for Conservation of Nature
NGO	Non - Governmental Organisation
WUA	Water User Associations (s)
WWF	World Wide Fund for Nature
ZEMA	Zambia Environmental Management Agency
ZESCO	Zambia Electricity Supply Corporation
ZMD	Zambia Meteorological Department
MTENR	Ministry of Tourism, Environment and Natural Resources.
FDC	Flow Duration Curve
USGS	United States Geological Survey

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1. INTRODUCTION

1.1 Background

There is growing worldwide concern about the impacts of land use change on the flow regime. However, as observed by Cloud (2007), measuring the effects of these human activities on the hydrologic regime is most of the times overlooked until a disaster occurs. A common person may only observe the impacts of land use changes in times of drought or when their property is damaged by floods.

Many changes have occurred to land use in Chongwe catchment in Zambia. Major changes have been in the reduction of forest cover (deforestation), urbanisation especially around the Ngwerere tributary, increased water abstraction for irrigated agriculture, and increased population pressure in general. Deforestation especially in forest reserves and in customary lands has mainly been driven by the high demand for cooking energy in Lusaka City in addition to poor forest management practices that engulfed Zambia since the 1980s. In this regard, Chidumayo (2009) has identified three periods of forest management in Zambia: (i) a period of good forest management (before 1980), (ii) a period of declining forest management (1980 to 1989) and (iii) a period of 'no forest management' (1990 to date). Further details are given by Chidumayo et al. (2001) and Chidumayo (2009).

Since the early 1990s, conflicts over water use have persisted in Chongwe catchment especially among the commercial farming community upstream and the villagers downstream (Mucheleng'anga et al., 2002; Chongwe District Council, 2006).

Thus, it can be said that apart from poor forest management and landscape management in general, water resources management has not been any better in Chongwe catchment. As observed by Ullendal et al. (2011), lack of accurate hydrological data is one of the main challenges affecting the sustainable utilisation of available water resources in Zambia as a whole. In this regard, inadequate understanding of the hydrologic regime of Chongwe River following increased human intervention in the catchment, possess a challenge to water allocation, utilisation and management in the area. This study therefore analysed the changes in the hydrologic regime following increased human intervention in Chongwe catchment. The study was focused on the upper part of the catchment which is above the confluence with Chalimbana tributary.

1.2 Statement of Problem

Chongwe catchment has been affected by increased conversion of forest for Charcoal production, agriculture and settlement. Commercial cultivation and irrigation are also dominating (Baumle et al., 2012). As a result, conflicts over water use among the commercial farming community upstream and the villagers downstream have persisted since the early 1990s (Mucheleng'anga et al., 2002; Chongwe District Council, 2006). Of concern is that, the impacts of these land use changes on the hydrologic regime of the main Chongwe River have not been adequately researched. Published literature shows only a paucity of related studies on Chalimbana tributary which joins Chongwe in the middle catchment (e.g Thesis by Sakeyo, 2008). And even on Chalimbana tributary itself, the focus by Sakeyo (2008) seems to have been only on the annual streamflow generation. However, annual streamflow alone is inadequate as it conceals the changes that have occurred within the annual cycle (wet vs dry season flows). This current study contributes to filling the gap in literature, by analysing changes on wet and dry season flows in addition to annual runoff generation following land use changes in the upper catchment of Chongwe (above the confluence with Chalimbana). Such information could enhance decision making regarding land use planning and water resource management (especially water rights allocation) in Chongwe catchment.

1.3 Aim

The aim of this thesis was to investigate the influence of land use changes on the water regime of Chongwe River (including its Ngwerere tributary).

1.3.1 Objectives

1. To examine the variations in climatic and hydrological time series data in Chongwe upper catchment.
2. To assess the changes in runoff generation using runoff coefficients before and after significant land use impacts.
3. To analyse the changes in wet and dry season flows.

1.4 Research Question

How has the hydrologic regime in Chongwe upper catchment responded to land use changes in the area?

1.5 Significance of the Study

Improved understanding of the impacts of land use / land cover changes on Chongwe river hydrological regime will be useful in the planning and design of water retention structures which is currently lacking in the basin as observed by Mucheleng'anga et al. (2002). The findings are also expected to be useful in ensuring sustainable management of the catchment especially its headwaters; as well as help in securing fair allocation of water rights for both upstream and downstream users, including the environment which is also a water user. Potential users of this information include; The Department of Water Affairs (DWA) in Zambia, the Water Board which is known as the Water Resources Management Authority under the new water law (Water Resources Management Act, 2011). Other potential users include the Water User Associations (WUAs) in the area, Zambia Environmental Management Agency (ZEMA), parties interested in environment flow management such the World Wide Fund for Nature (WWF), Non-Governmental Organisations (NGOs) operating in the area and the research community.

2. LITERATURE REVIEW

2.1 Introduction

This chapter discusses the findings of several scholars on the impact of landuse / land cover change on the hydrological regime. A brief discussion of the water sector in Zambia is also given.

2.2 Land use change and hydrologic effects

As observed by Swanson (2002), Hydrologists have long been challenged with the need to identify and record anthropogenic impacts on the natural flow regime of streams and rivers. Bosch and Hewlett (1982) point out that the first catchment experiment aimed at investigating the effect of forest management practices on water yield was set up in 1909 at Wagon Wheel Gap in Colorado, USA. A brief review of such studies is therefore given below.

2.2.1 Effects of Afforestation and Deforestation on annual water yield

Forest cover changes are among the most important land use changes impacting the hydrologic cycle. For those who like partitioning, we can distinguish the impacts of afforestation from those caused by deforestation as discussed below.

Effects of Afforestation on water yield

Several scholars (Sahin and Hall, 1996; Hibbert, 1967; Fahey and Jackson, 1997; Bosch and Hewlett, 1982; Buytaert et al., 2007; Zhang et al., 2007; Yao et al., 2011) have reported a decrease in water yield following afforestation; hence suggesting that in general, increase in forest cover reduces water yield.

For example, in the Qiaozidong catchment of China, Zhang et al. (2007) found decreased runoff coefficients in the recent period with more forest (1995-2004) compared to the previous period (1986-1994) that had less forest.

Effects of Deforestation on water yield

On deforestation, Bosch and Hewlett (1982) ex. Langfold (1976) found no significant increase in water yield immediately after burning a Eucalyptus stand, but he reported a decrease in streamflow after regrowth of the stand.

On the other hand, several scholars (Sahin and Hall, 1996; Hibbert 1967; Bosch and Hewlett, 1982; Mahe et al., 2004; Lenhart and Neiber, 2011a; Lenhart et al., 2011b; Pena Aranchibia, 2012) report an increase in water yield after forest removal. For example, Lenhart and Neiber (2011a) found an increase in Q: P ratios (runoff coefficients) in the Upper Midwest watersheds that have less forested. They attributed the increase in runoff coefficients to land-use change and to increased tile drainage in that area of Minnesota. Additionally, Lenhart et al. (2011b) found increased Q: P ratios in agricultural watersheds of the Midwest. They concluded that the increase in Q: P ratios was mainly due to land use (agriculture) and that the high Q: P ratios contributed to greater flow volumes in the agricultural watershed.

In Zambia, Sakeyo included the use of runoff coefficients in his HBV modelling work on Chalimbana River. He calls them Qrec/P ratios (Qrec meaning Qrecorded). He found a 33 % increase in runoff generation due to deforestation in Chalimbana.

A brief appraisal of the main processes at work in influencing change on water yield

The effects of vegetation change on annual water yield vary from region to region depending on among other things; vegetation type, climate, as well as catchment area (Bosch and Hewlett, 1982). In this regard, Bosch and Hewlett (1982) explain that yield changes (decreases/increases) are highest in high rainfall areas. They further point out that the effect of clear cutting on water yield in these high rainfall areas is short-lived than in low rainfall areas due to rapid vegetation regeneration. That is, Bosch and Hewlett (1982) contend that changes in water yield are more persistent in drier areas due to slow vegetation recovery. However, they caution that these results seem to be directly related to precipitation in the treatment years. In this regard, Bosch and Hewlett (1982) suggest the need for more years of calibration and treatment to evaluate the effect of wet and dry years on the expected changes in streamflow in dry areas. They correctly observe that these dry areas are the ones facing persistent conflicts involving upstream and downstream water users and often, the forestry practice comes under intense criticism. There is also a view that water yield increase after forest cutting is related to the location of such cuttings, especially with respect to the source area of stream flow (ibid).

Several scholars, including; Zhang et al. (2001); Brown et al. (2005); and Li et al. (2007) have pointed out that evapotranspiration is the main process responsible for changes in water yield following vegetation change. This holds at the mean annual scale or long time scale. Additionally, several scholars (including Bruijnzeel, 1990; Peña Arancibia, 2012) have shown that changes in infiltration capacity following vegetation change also play a key role on the hydrologic regime.

As observed by Peña Arancibia, (2012), forest plays two major roles; thus forests act as ‘pumps’ through evapotranspiration and also as ‘sponges’ by improving infiltration rates. Forests also improve moisture retention due to organic matter while their root network improves soil physical properties (ibid). This means that at least three hydrological parameters; Evapotranspiration, Infiltration and the water holding capacity of the soil are important in deciding the fate of the hydrologic regime after forest change.

2.2.2 Effects of Afforestation and Deforestation on peak flows

Regarding, the effects of Afforestation and Deforestation on dry and wet season flows; Brown et al. (2005) explains that in the tropics or summer rainfall areas, results vary from uniform changes across all seasons to large changes in dry season flows. There seems to be consensus that deforestation increases annual water yield and peak flows (wet season flows) while afforestation does it vice versa.

2.2.3 Effects of Deforestation on dry season flows: Conflicting results

There seems to be no consensus regarding the effects of deforestation on dry season flows. Some scholars report increases while others report decreases in dry season flows after deforestation. Further discussion on this subject is given below.

Decrease in dry season flows

Scholars (such as Buytaert et al., 2004 and Buytaert et al., 2007) have reported decreases in dry season flows following deforestation. Authors that have observed reduction in dry season flows after deforestation have attributed such decreases to reduced infiltration opportunities, which in turn cause reductions in base flow which is supposed to recharge the stream in the dry season.

Reduced water holding capacity of the soil (due to forest removal or conversion to agriculture, including land degradation) has also been blamed for decreases in dry season flows. For example, in cultivated areas, Buytaert et al. (2004) and Buytaert et al. (2007) observed a remarkable reduction in lows in a cultivated catchment compared to a forested one. They attributed the observed reduction in low flows to a much faster release of water in the cultivated catchment, thus causing base flow to fall much more rapidly compared to a forested catchment (ibid).

Increase in dry season flows

On the other hand, some scholars (for example Yao et al., 2011; Molina et al., 2012) have observed increases in dry season flows after deforestation. They point out that the increases in dry season flows are due to water gains arising from reduced evapotranspiration losses (including reduced interception loss) due to forest removal. They claim that even if the forest is replaced by grass or agricultural crops, there will still be some water gains since forest have more evapotranspiration rates due to their larger crowns and deeper penetrating roots compared to grass and crops.

Examples of this view can be given by Yao et al. (2011), who observed a reduction in both peak and low flows in north-eastern China after afforestation. Hence, the reduction in peak flow was attributed to increased evapotranspiration loss after afforestation. A similar occurrence was observed elsewhere, for example, Molina et al. (2012). This suggests that recommending tree planting as a means of conserving or increasing base flow may not hold in such regions.

Resolving the conflicting results on dry season flows

Bruijnzeel (1990) noted the following regarding the impacts of vegetation changes on dry season flows in the tropics;

- The conflicting evidence concerning the impact of forest change on the flow regime can be resolved by looking at the net effect of changes in infiltration opportunities and evapotranspiration (ET).
- If infiltration opportunities after deforestation decrease to the extent that the increase in volumes of storm flow exceed the increase in base flow associated with reduced evapotranspiration (ET), then dry season flow will decrease. In this regard, the reduced infiltration capacity can generally be held responsible for the deterioration of streamflow regimes so commonly observed in the tropics.
- In contrast, if surface infiltration capacity is maintained after forest removal, either due to a fortunate blend of stable soil aggregates and low rainfall

erosivity, or by thoughtful soil conservation practices, then the reduced evapotranspiration (ET) after deforestation will actually result in increased base flow.

- The impact of reforestation/afforestation on dry season flows will depend on both the balance between changes in infiltration and evapotranspiration, and on the available water storage capacity of the soil.

Bruijnzeel (1990) further notes that the benefits of increased dry season water yield are more than offset by increased stream sedimentation rates in most cases.

2.2.4 Impacts of Urbanisation on the flow regime

Urbanisation has been shown to increase both runoff and peak flow volumes as pointed out by Chow et al. (1988).

On the other hand, it leads to reduction in dry season flows (low flows). Spinello and Simmons (1992) found an increase in peak flows and a reduction in base flow in urban and sewer areas. This was principally due to the lowering of the water table following urbanisation. They observed that, in urban areas, there is an increased amount of impermeable area, thus resulting in direct routing of runoff in to the streams through storm sewers and sanitary sewers. This prevents water from entering the ground water system.

2.2.5 Hydrological modelling: The case of Agriculture dominated catchments

Most of the results given above are from paired catchment studies while others are from time series analysis (including trend analyis, Linear regression, Runoff coefficients, flow duration curves and plots of mean monthly flows and so on). Some authors of these articles have claimed that using actual data has an advantage over hydrological modelling; in that actual data has less uncertanities compared to models.

However, hydrological models are still valuable tools for simulating rainfall-runoff processses. They enable easy analysis of the hydrologic regime under various landuse/landcover scenarious and climate change. They also enable forecasting of the impacts on the flow regime. They are therefore useful tools for assessment, management and planning of rainfall-runoff processes. Hence this section gives a brief review of some key findings of hydrological modelling studies in Africa as a whole and in Zambia.

The results are generally consistent in agricultural dominated catchments of Africa. Opera and Okello (2011), using the SWAT model on Nyando River basin (3600 km^2) in Kenya, found highest values in both the mean and peak flows under the scenario where agriculture was dominant. They attributed this to less moisture deficit in agricultural lands (since crops demand less soil moisture), hence the moisture deficit in agricultural lands is satisfied much faster and results in increased streamflow than in forest where the moisture deficit is high. A similar study was conducted in Ethiopia by Surur (2010), who applied the SWAT model on the Beles basin (13, 959 Km^2) using land use data for three different years (1986, 1999 and 2004). In this period, Surur (2010), found a decrease in forest land and an increase in agricultural land. This in turn caused an increase in streamflow. The increase in streamflow was attributed to the decrease in evapotranspiration and soil retention of the area under agriculture (ibid).

Still in Ethiopia, one more interesting study is the MSc thesis by Geremew (2013), who found an increase in mean monthly streamflow for wet months, and a decrease in dry season flows (streamflow for dry months) due to forest conversion to agriculture. This study is interesting because the previous two cases studies only analysed the impacts at an annual time step. Sakeyo (2008), in his MSc thesis, used the HBV model to analyse the impacts of deforestation on streamflow of Chalimbana river catchment in Zambia. Chalimbana River is one of the tributaries of Chongwe River. However, in this thesis it is regarded as outside the study area as it joins the main Chongwe River almost in the middle of Chongwe catchment. Sakeyo (2008) found an increase in runoff generation after a 30 % forest loss in Chalimbana catchment.

2.2.6 Impacts of Land use change on flow regime under reduced precipitation

Several scholars have reported increases in runoff despite reduction in precipitation. Scholars seem to agree that this is due to reduced infiltration rates that accompany land use changes (increased imperviousness). Examples on this subjected are briefly discussed below.

In the Andean region of Ecuador, Molina et al. (2012) analysed the time series of streamflow and rainfall data from 1979/1982 to 2005/ 2007. They found significant increases in discharge data despite decreases in rainfall. They argue that since changes in discharge and in precipitation are opposite, the increase in discharge cannot be explained by a decrease in precipitation. In this regard, they point out that the removal of native forest for rangeland or croplands in that particular area of Ecuador could have contributed to the increase in total annual water yield through an increase in base flow. This stems from the argument already discussed above; that there are usually less evapotranspiration losses following vegetation removal.

However, in most parts of Africa, reduced infiltration opportunities seem to be the major causes of increased runoff after deforestation. For example, despite the severe drought experienced since the 1960s in the Sahelian region of West Africa, many scholars such Descroix et al. (2013) have observed significant increases in runoff coefficients and a general increase in stream discharges during the same period that precipitation decreased. Hence, they termed the phenomenon as 'Hydrological Sahelian Paradox'. This increase in runoff coefficients and runoff in general has been attributed to land use change through reduced infiltration opportunities (Descroix and Amogu, 2012 and the references therein). *The Sahel is a semi-arid climatic Zone between the Sahara desert to the northern part of Africa and the Sudanian Savanna to the south.*

In Burkina Faso (part of the Sahel in West Africa), Mahe et al. (2004) also found an increase in runoff and peak flows despite a reduction in rainfall and an increase in the number of dams in the Nakambe river basin. This was attributed to the decrease in forest and an increase in the cultivated area and an increase in the amount of bare land. Kashaigili (2008) in Tanzania, neighbour to Zambia, used time series analysis and did not find any significant decreasing or increasing trend in both rainfall and runoff. He however observed a significant reduction in dry season flows which he attributed to reduced infiltration rates after deforestation. He therefore noted that the non-significant trend in annual runoff could have been due to the greater reduction in dry season flows compared to wet season flows which did not change.

2.3 The Water Sector in Zambia

2.3.1 Water Rights and Water Allocation in Zambia: An Overview

According to the Water Resources Management Act No. 21 of 2011 as amended, the ownership of all water in Zambia is vested in the President (as opposed to the state) on behalf and for the benefit of all Zambians. A person does not own any water in its natural state. Among the principles of water resources management in the Act; is that water is a basic human need and as such domestic and non-commercial needs enjoy priority of allocation use.

The Water Resources Management Act No. 21 of 2011 as amended recognises the environment as a water user which should enjoy priority of allocation in water use second to the basic human need. The Act further provides equitable access to water. It further recognizes that water has an economic value and social value. Thus, water has both an economic cost and an administrative cost of facilitating its use and that these costs should be reflected in the charges for water permits for the right to use water for economic purposes. But all domestic and non-commercial uses of water in Zambia are not required to obtain a water permit. The Water Resources Management Authority Board has been mandated by the said Act to allocate water entitlements and apportion water for various uses.

Chileshe et al, (2005) observed that water rights in Zambia are linked to the right of occupancy or title to the land where the water body is located. However, in the Water Resources Management Act No. 21 of 2011 as amended, this seems to have been changed as the Act states that the location of a water resource on land does not confer preferential rights to its use.

Ullendal et al. (2011) point out that the allocation of water in Zambia has faced a number of challenges as well as conflicting interests for the available water resources. The challenges include lack of accurate hydrological data for optimum allocation of water amongst all users (ibid). Ullendal et al. (2011) further bemoan the Zambian government priority which has in the past tended to focus on specific economic sectors, such as hydropower production and irrigated agriculture. They contend that this has undermined the potential of other sectors related to development; especially small-scale farmers who represent the larger population, and provide two-thirds of the annual staple food harvest. They argue that these small scale farmers should be the prime beneficiaries of water according to the poverty alleviation and food security strategies.

Ullendal et al. (2011), further observe that, currently the fragmented institutions in the water sector are unable to provide the emergent farmers with the needed access to water. Hence small scale farmers have no option but to abstract water, which authorities dim illegal. Equitable and transparent allocation of water amongst all stakeholders is thus needed (ibid).

2.3.2 Environmental Water Concern: The case of Environmental Flows in Zambia

The environmental flow concept is relatively new. It stems from the growing worldwide concern that land use changes have resulted in unprecedented impacts to riverine ecosystems (Tharme, 2003). To this effect, Environmental flows refer to the quantity, the quality including the timing of water flows required for sustenance of freshwater and estuarine ecosystems and the human livelihoods and wellbeing that depend on them (Brisbane Declaration, 2007; Forslund et al., 2009).

In Zambia, the World Wide Fund for nature (WWF), the Zambian government and the Zambia Electricity Supply Corporation (ZESCO) have been working on the development of environmental flows in the Zambezi river basin for several years (Schelle and Pittock, 2005; Forslund et al., 2009; Mertens et., 2013). This effort led to the KAFRIBA model and the modification of the Itezhi-tezhi dam operating rules in 2004 on the Kafue River.

However, there is need to conduct a detailed and systematic assessment of environmental flows for the whole country since the KAFRIBA model was developed specifically for the Kafue River Basin; hence not applicable to other catchments. There is also need to assess the benefits of the freshets released so far on the ecology and water quality of the Kafue River. Even though the issue of environmental flows may be relevant in Chongwe catchment, determination of environmental flow needs is beyond the scope of this thesis study. But it is certainly an interesting area for future studies.

3. DESCRIPTION OF THE STUDY AREA

3.1 Introduction

This chapter gives the location, along with the physical and socio-economic characteristics of the study area.

3.2 Location

Zambia is a sub-tropical country located in the central part of Southern Africa. The Chongwe River mainly lies in Chongwe District of Lusaka Province in Zambia. However, its source is in Chisamba district of Central province. Some of its tributaries such as the Ngwerere originate from Lusaka city, Zambia's capital and are thus highly influenced by urbanisation. Having a catchment area of 5,150 km^2, the Chongwe River flows southward into the Zambezi (Baumle et al., 2012). Apart from the Ngwerere, other tributaries of Chongwe River are Kanakantapa, Chalimbana and Luimba River. The Chongwe catchment can be divided into three sub catchments, namely; the upper catchment, the middle and the lower catchment.

This study focusses only on the upper Chongwe catchment (Figure 3.1). The study area was delineated using the digital elevation model in ArcGIS 10.2. This study takes the upper Chongwe catchment to be the area above the confluence with Chalimbana tributary. Hence, the delineated study area covers an area of 2006.6 km^2. With respect to administrative boundaries, the northern part of the selected study area covers small parts of Chisamba district in the headwaters, while the western part covers a portion of Zambia's Capital City, Lusaka. However, the majority of the study area is in Chongwe district.

3.3 Hydrology

The main tributaries of Chongwe River in the selected upper catchment are Ngwerere and Kanakantapa (See Figure 3.1). However, since there is no flow data on the Kanakantapa, the study focussed on Ngwerere which had flow data from 1955 to 2005 at Ngwerere weir. The study also focused on the main Chongwe River which had flow data from 1968 to 2005 at Chongwe 5025 hydrological station (Great East Road Bridge). Due to its downstream location, Chongwe 5025 was taken as the outlet of the selected study area.

The Ngwerere weir was very important in this study because it does not have much water abstractions upstream. Therefore the flows recorded at this weir reflect the effects of urbanisation in Lusaka city on the hydrologic regime. This is so due to increase in urban development upstream the weir. On the other hand, the Ngwerere weir has long enough records dating back to as early as the 1950s and thus provides a better estimation of baseline conditions (period with less human impacts).

There are many dams downstream the Ngwerere weir but upstream the chosen outlet station of Chongwe 5025. In other words, Chongwe 5025 is affected by a lot of factors ranging from water abstraction and impoundments upstream, to deforestation. The Ray's dam on the Chongwe River is the largest in the catchment (about 8 km^2) and it is upstream Chongwe 5025. This dam is one of the developments in the catchment in more recent years. The majority of dams in the area are less than 1 Km^2. Most of these dams, including the Rays dam are used for irrigated agriculture in the catchment.

According to Chongwe District Council (CDC, 2006), the major threats to the hydrology of Chongwe, particularly, to stream flow include; increased water demand by the commercial farmers and local people. They point out that the use of water in the area has been contentious since the early 1990s especially between commercial farmers and the local communities downstream. They further point out that cultivation along the river banks, deforestation and sand mining pose major threats to the flow regime.

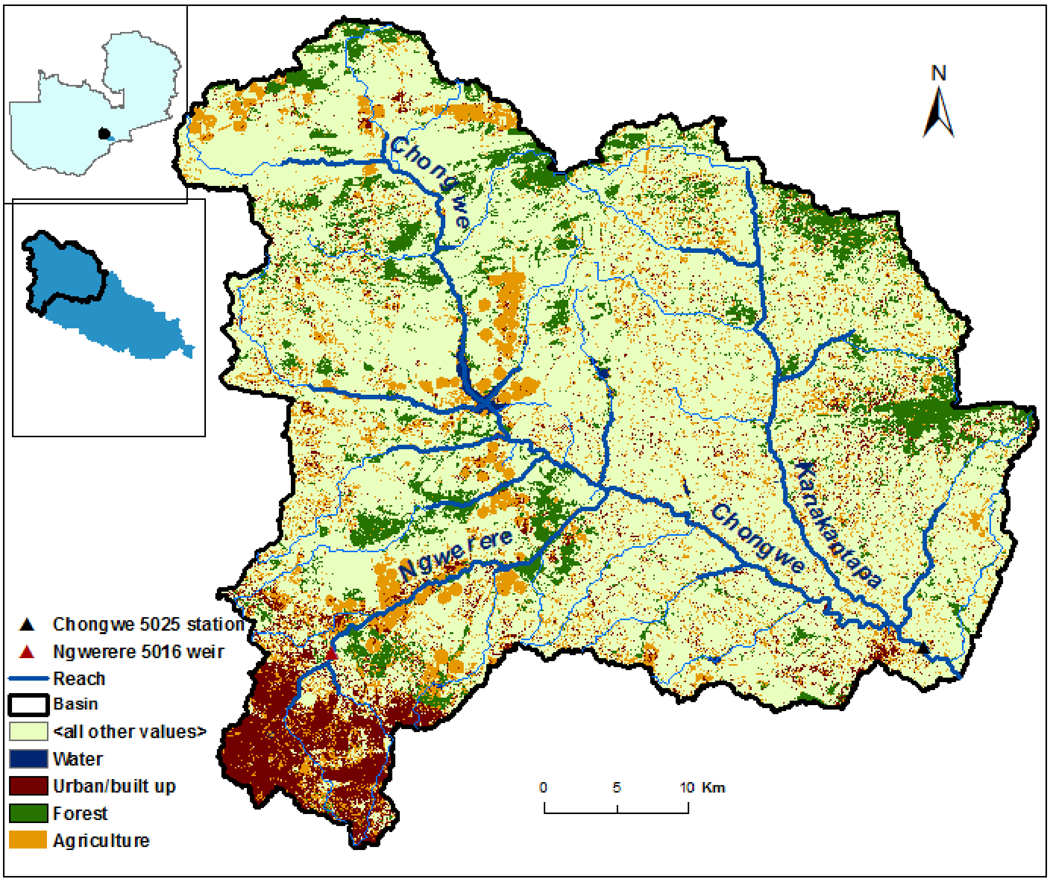


Figure 3.1: Location of the study Area

Catchment and river network derived from analysis of DEM in ArcGIS 10.2 and Landuse information from the analysis of 2008 Landsat images obtained from the USGS. MSc thesis, 2012.

3.4 Climate

According to the Koppen – Geiger Classification, the predominant climate in Zambia is *Cwa,* which means the climate is humid subtropical, with dry winters and hot summers. The remaining small patches have Tropical wet and dry (savanna) climate (*Aw*). Additionally, there is a small portion of semi-arid steppe *(Bsh)* in the south-western part of the country.

Zambia's climate is characterised by a clear division into dry and rainy season. According to Nieuwolt (1971), this clear division between the dry and rainy season is due to the combined effect of low latitude, continental position and high elevation above sea level.

Accordingly, there are three distinctive seasons prevailing in Zambia, namely;

1. Rainy season – warm wet season from November to April.

2. Cold season – cool dry season from April to August.

3. Hot season – hot dry season from September to October.

The southward shift of the Inter-Tropical Convergence Zone (ITCZ) is so important in as far as the rainy season in Zambia is concerned. The ITCZ is simply an area of pronounced convective activity resulting in to heavy tropical rain.

During the dry season, the ITCZ is situated over the Sahel region at around 15°N; hence Zambia is dry around this time since the country lies between 8-17 degrees south of the equator. But following the apparent movement of the sun, the ITCZ shifts southwards to about 17°S around January.

In this regard, the trade winds of both hemispheres converge into the low pressure area over the ITCZ. The winds involved are the South-East Trade winds, the North-West Trade winds or Congo Air Mass and the North-East Monsoons. The Congo air coming through the North-West brings more rainfall to Zambia compared to the other two winds because of its high moisture content. In this way, the resulting convective activity produces some heavy tropical rain. Rainfall in Zambia is also influenced by altitude and by the El nino Southern Oscillation (ENSO) with La Nina years being wetter than normal. Due to above factors, rainfall is highest in the Northern part of Zambia and decreases southwards.

3.5 Temperature and Sunshine

The mean annual temperature in Lusaka Province where the study area is located is 20.7°C; with June and July being the coldest months at about 16°C (Baumle et al., 2012). The month of October has the maximum monthly temperatures averaging 24°C. The average Sunshine duration is about 7.7 hours (ibid).

3.6 Rainfall

The mean annual rainfall in Chongwe catchment fluctuates between 750 mm and 880 mm. According to Baumle et al. (2012), annual rainfall over a thirty-year period from the 1980/1981 to 2009/2010 seasons at the meteorological stations varied between 801 mm at Lusaka City Airport and 827 mm at Kenneth Kaunda International Airport, while the average number of rainfall days per year is approximated to be 77 days.

3.7 Evaporation

The amount of water that could be evaporated and transpired if there was sufficient water available is called Potential evapotranspiration (PET). The PET values range from 1,530 – 1,590 mm as obtained using the revised Penman equation in the Zambia National Water Resources Master Plan (Baumle et al., 2012). Baumle et al. (2012) contends that these calculations for PET could be generally higher than estimated.

On the other hand, Baumle et al. (2012) observe that the Actual Evapotranspiration from vegetated land is much lower than PET due to the drying out of surfaces and soils between individual rainfall periods and also during the dry season. Hence Actual Evapotranspiration varies between 730 mm and 739 mm as calculated by the Turc (1961) equation in the National Water Resources Master Plan (ibid). Again, Baumle et al. (2012) suggest that Actual Evapotranspiration in the area could be much lower (less than 500 mm) if crop-specific transpiration and soil physical properties are taken into account when computing Actual Evapotranspiration.

The Long-term Class A pan evaporation at Lusaka International Airport is about 2,331 mm. This value, when multiplied by the pan evaporation coefficient of 0.75 gives 1,748 mm as Evaporation from open water bodies (ibid).

The net evaporation (mean rainfall - PET) has negative values for the most part of the year except for December to February (ibid). The negative values are due to high temperatures and a long dry season.

3.8 Soil type, Geology

The main landforms in Chongwe include; the plateaux, hills, escarpment and valleys. The geology comprises of gneiss, schist, quartzite, limestone and shale (mainly in the south-western parts).

According to Baumle et al. (2012), soil types in Chongwe Catchment include;

1. Leptosols mostly on hilly areas of the catchment and on the escarpment as well as extending towards the southern part of the catchment. These Leptosols are very shallow and stony soils, although they can be gravelly and well drained.

2. Acrisol and Leptosol combination – An association of Acrisol and Leptosol is very common on the undulating areas as well as on the hilly parts of the catchment.
3. Lepsol and Lixisols combination. These are found mainly in hilly parts and at transition to escarpment. They are associated with schist and psammites.
4. Alisols and Acrisols combination. These are found on undulating terrain or on gently sloping hills especially near the Kenneth Kaunda International Airport.
5. Phaeozem. They are associated with wet grasslands and forest areas which have a humus-rich surface horizon. They only cover a very small part of the catchment in flat or undulating areas.
6. Vertisols. These probably cover the smallest part in the catchment. They are found in the northern part of the catchment.

3.9 Topography

The elevation drops from about 1,180 meters above sea level (asl) from the Chongwe headwaters to about 1,000 meters asl in the middle catchment. The elevation continues to drop southwards reaching 365 meters asl near the confluence to the Zambezi River.

3.10 Vegetation and land use

The most common vegetation types in Chongwe Catchment are the Miombo woodland and Munga woodland (Vegetation Map of Zambia, 1976).

Munga woodland is an open, park-like, one- to two storeyed savannah woodland with up to 18 meters high individual deciduous trees. Munga means “thorn” in one of the local languages. On the other hand, **Miombo** is a woodland with two storeys, dominated by semi-evergreen trees ranging from 15 to 21 meters high. According to Chidumayo et al. (2001), the most common Miombo woodland trees are of *Brachystegia, Julbernardia* and *Isoberlinia* species. Mopane woodland also persists in the lower Zambezi valley where the climate is hotter and drier. This area has some scattered baobab and palm trees in addition to Mopane.

The major threats to natural vegetation in the catchment have been extensive agriculture and Charcoal production. The Miombo woodland trees (*Brachystegia,* *Julbernardia* and *Isoberlinia* species) have been the most vulnerable for charcoal production. Chidumayo et al. (2001) and Chidumayo (2009) observe that despite the Miombo woodland having the potential to regenerate; it faces challenges owing to; lack of proper forest management since the 1980s, and also due to the conversion of forest reserves to urban and agricultural areas. Decreasing rainfall trends add to the problem. Further, there have been no significant efforts to venture into tree planting. Grass is also predominant in the water-logged areas especially in the dambo areas, along the rivers and streams and in the floodplains.

3.11 Economy

Commercial irrigation agriculture by private investors has been on increase in the area in recent years. However, most of the indigenous people are mainly dependent on subsistence agriculture, gardening, Charcoal burning and sand mining for their livelihood.

Chidumayo et al. (2001) have reported that 85% of the rural population in Chongwe were actively involved in agriculture in 1991. The authors rightly observes that despite agriculture being the main economic activity in the area, incomes from the sale of agricultural produce have declined over the past two decades owing to the removal of agricultural subsidies by government and to the liberalization of agricultural marketing.

3.12 Population

The Central Statistical Office (2004 and 2012), point out that the population of Lusaka province grew at an average annual growth rate of 6.3 percent between 1969-1980, 3.6 percent between 1980-1990, 3.4 percent during the period, 1990-2000 and 4.6 % during the period from 2000-2010. Table 3.1 and Figure 3.2 show the long term population of Lusaka City and Chongwe district since the study area covers a considerable part of these two.

Table 3.1: Population of Lusaka City and Chongwe district from 1969-2010

Year	Lusaka City	Chongwe district
1969	262,425	-
1980	535,830	63 848
1990	761,064	95 738
2000	1, 084, 703	137461
2010	1, 747, 152	192 303

Source: CSO 2004, 2012 ; Chidumayo et al., 2001; Mulenga, 2003.

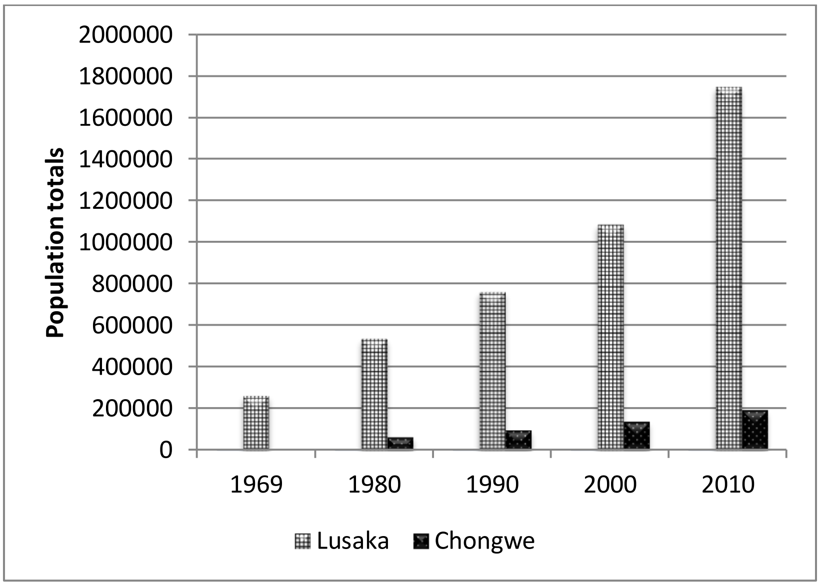


Figure 3.2: Population of Lusaka City and Chongwe district from 1969-2010

MSc thesis 2014, (figures from CSO 2004, 2012 ; Chidumayo et al., 2001; Mulenga, 2003).

4. METHODOLOGY

4.1 Introduction

This chapter discusses the materials used and their sources. It further describes the data analysis methods that were used to achieve the objectives of the study.

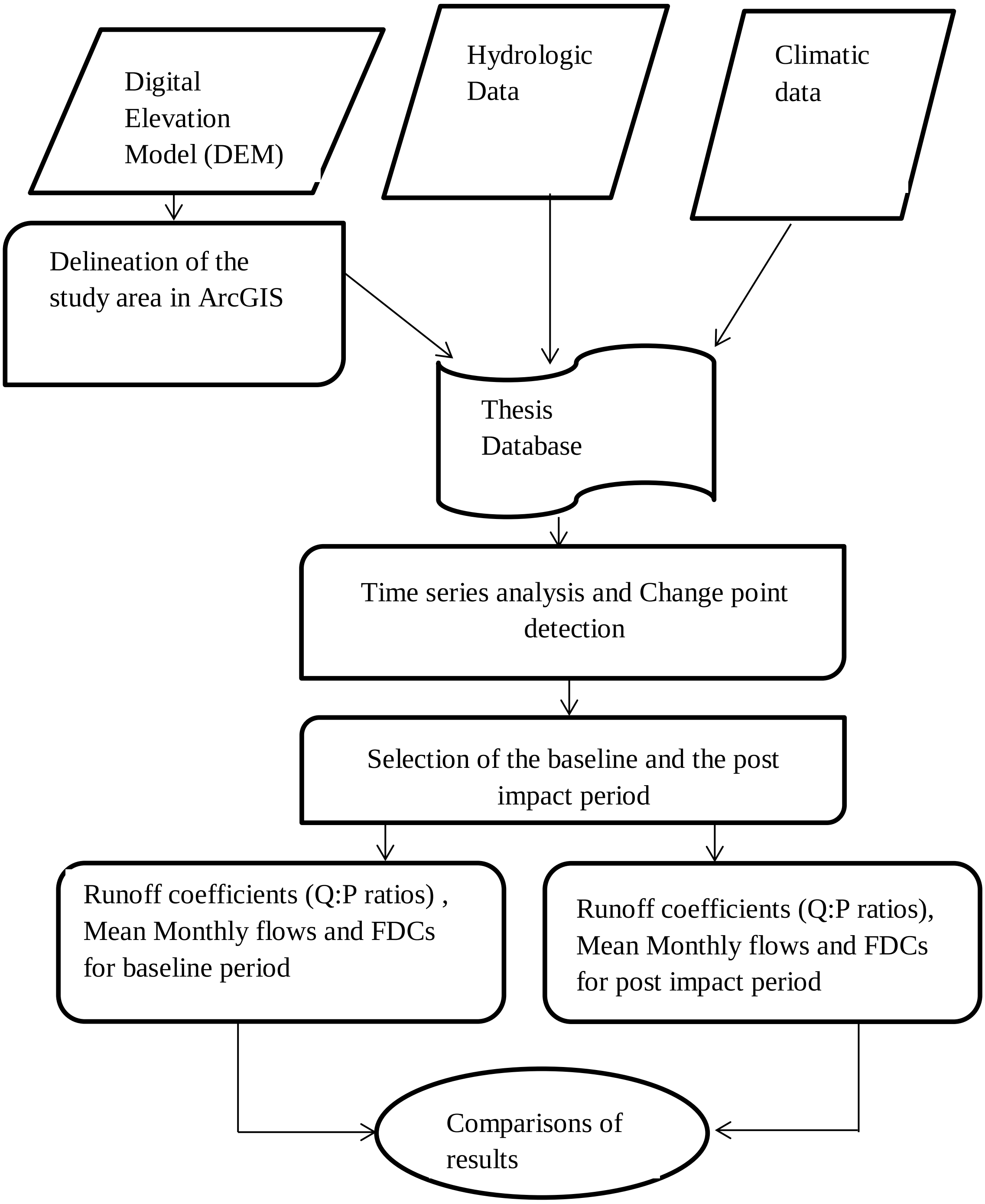


Figure 4.1: Methodological Flow Chart

4.2 DATA SOURCES

The following data were collected for this study; Digital Elevation Model (DEM), Hydrological data (daily discharge data), and Climatic data.

4.2.1 Digital Elevation Model

The Digital Elevation model (DEM) was obtained from the World Coverage map available at viewfinderpanoramas.org. The Digital Elevation Model (DEM) was analysed in ArcGIS 10.2 for the purpose of obtaining the boundary of the study area, including obtaining information about the size of the catchment. The area covered by each station is also crucial when computing runoff coefficients.

4.2.2 Hydrological Data

Daily streamflow data was collected from the Department of Water Affairs (DWA) in the Ministry of Mines, Energy and Water Development in Lusaka, Zambia. The data was collected for the Ngwerere at Ngwerere weir and main Chongwe at Chongwe 5025 from the time of the start of records at each station up to 2006. Table 4.1 shows the length of the discharge data at each station.

Table 4.1: Discharge data in the study area since start of records up to 2006

Station	Area (Km^2)*	Time step	Period	Length of record
Ngwerere (5016)	303	daily	1955-2006	51 years
Chongwe (5025)	1813	daily	1968-2006	38 years

* The area covered by each station is based on DWA calculations provided along with the discharge data.

4.2.3 Meteorological Data

Weather data (Table 4.2) were obtained from the Zambia Meteorological Department (ZMD).

Table 4.2: Climatic data at meteorological stations in the Upper Chongwe Catchment

	Kenneth Kaunda International Airport	Lusaka City Airport
Rainfall	1970-2006 (monthly time step)	1973-2006 (monthly time step)
Temperature	1970-2006 (monthly time step)	1973-2006 (monthly time step)

Only 12 years of daily weather data (2000-2012) was provided by the ZMD. Thus, it was not possible to obtain daily climatic data at the two stations for a much longer period.

An attempt was made to generate daily weather data using the obtained monthly data. The results were successful at a monthly time step, but not very successful on a daily time step with regards to the frequency and magnitude of daily rainfall events. The challenge was that the monthly data provided by ZMD did not include the exact number of rain days which are required when correcting for the frequency of rainfall events in a month. Efforts were made to generate daily weather data from the monthly data. These efforts (use of weather generators and global weather data), though unsuccessful, are summarised below.

4.2.4 Weather Generators

Many hydrological models require daily climatic data as part of the inputs. However, in many cases, especially in Africa, the available climatic data either has gaps or the length of records is not long enough to make meaningful hydrological simulations. Further, due to the growing concern regarding the impact of land use change on water resources, it has become inevitable to forecast future impacts of such changes on the hydrology of watersheds using forecasted daily climatic data. Hence, Weather

Generators provide a solution to the aforementioned problems by helping simulate daily climatic data.

There are many Weather Generators; some of which simulate daily data from Monthly weather such as MODAWEC and SIMMETEO weather generators. On the other hand, some Weather generators require not less than 20 years of daily climatic data to estimate the parameters that are then used for simulation of daily data. Examples of such Generators include the WGEN and WXGEN weather generators. Additionally, some weather generators such as the CLIMGEN are slightly flexible in that they can use available daily or monthly climatic data to perform the weather simulation. Below is a brief discussion of on the theory of some of the weather generators that were explored in this study.

WXGEN Weather Generator

The WXGEN weather generator model is built – in in the SWAT model as well as in many other models. It is used to either generate daily climatic data or to fill in the gaps in the observed data (SWAT theoretical document, 2009). Monthly statistics such as the monthly skew coefficient and monthly probability of wet day after dry day or wet day after wet day are the required inputs to WXGEN. But these monthly statistics need to be first calculated using available daily data, of which not less than 20 years period of record is recommended for much stable results. This makes it difficult to use WXGEN for areas without daily data.

Of all the weather elements, precipitation is the first to be independently generated in WXGEN. In order to do this, WXGEN uses a first-order Markov chain technique to make a wet or dry day decision. When a decision for wet day is made, the amount of precipitation is then generated using either a skewed normal distribution with three parameters (Nicks, 1974) or a one parameter exponential distribution. After independently generating precipitation for a day, WXGEN then goes on to generate Maximum temperature, minimum temperature, solar radiation and relative humidity based on the presence or absence of rain for the day (SWAT Theoretical document, 2009). Daily wind speed is generated independently.

MODAWEC (MOnthly to DAily WEather Converter)

This weather convert was developed for the EPIC model, but can be used to generate daily data for many other environmental models or uses. Its advantage over the

WGEN weather generator and similar models is that it uses Monthly weather data. Monthly weather data are easier to obtain than daily weather data. Required data for MODAWEC include monthly precipitation, maximum and minimum temperature, and monthly wet days in each year. The outputs are daily precipitation, daily maximum temperature, and daily minimum temperature.

The MODAWEC model converts monthly precipitation (in mm), including maximum and minimum temperature (in degrees C) to daily values while preserving the monthly totals and averages. MODAWEC model uses precipitation as the driving variable. The occurrence and amount of Precipitation are generated independently and other variables (e.g. temperature) are then generated based on the stochastically generated precipitation. Details about MODAWEC are provided by Liu et al. (2009).

An attempt was made to extend the daily weather data using the aforementioned weather generators. The results were not fruitful. This is because the weather generators, namely WXGEN, WGEN, and SIMMETEO require a minimum of 20 to 25 years of daily data for them to generate reliable long term data. Since the available daily data was only for 12 years, such weather generators could not be applied with success. The Monthly to Daily Weather Convertor (MODAWEC) did not also yield satisfactory results. This was due to lack of data on the number of wet days in a month, which are the required inputs in MODAWEC.

Global Weather Data (Satellite data)

Global weather data was downloaded from the Climate Forecast System Reanalysis (CFSR) website at http://globalweather.tamu.edu/ for the purpose of supplementing the observed weather data. There is one CFSR station (where the satellite recorded data from) and this station falls almost at the centre of the study area at an altitude of 1126m, latitude S15.14 and Longitude E28.44 (see figure 2 under the study area location section). The CFSR data are available for each day from 1979 to 2010 at a 38 kilometre resolution. Fuka et al. (2013) has observed that in some cases models that are forced by the CFSR data can simulate discharges that are as good as or even better than what the observed data from gauge stations could produce especially if such stations are more than 10 km from the watershed.

When compared to the observed data, the CFSR data (global data) tended to have higher peaks (higher values). There was also a problem with the number of rainfall events in the global data as it recorded rainfall even in some dry periods. There was therefore need to correct the CFSR data so as to preserve the monthly totals. Hence the monthly totals provided by the Zambia Meteorological Department became useful as they could help to correct the CFSR data. With the help of the thesis supervisor, the following method (equation 4.1 and 4.2) was developed;

$$Tlocal = \frac{\text{TGlobal}}{TGlobal\ month} Error\ (month) + TGlobal, \tag{4.1}$$

Where;

$Tlocal$ is the corrected satellite rainfall for a day, $TGlobal$ raw global rainfall for a day, and $TGlobal\ month$ is the global (satellite) monthly mean rainfall.

And

$$Error\ (month) = Monthly\ local\ rainfall - Monthly\ Global\ rainfall \tag{4.2}$$

Another attempt was made to correct rainfall using the Multiplicative shift method (equation 4.3) by Ines and Hansen, (2006);

$$xi' = xi\ \frac{\bar{X}obs}{\bar{X}glo} \tag{4.3}$$

Where; xi' is corrected satellite rainfall for a day, xi is raw satellite rainfall for a day, $\bar{X}obs$ is observed monthly mean rainfall and $\bar{X}glo$ is global (satellite) monthly mean rainfall.

These two methods produced exactly the same results. However, they both did not correct errors in the frequency distribution and in the actual intensity of rainfall on a daily scale. Thus, the corrections were only on a monthly scale.

In conclusion, the global weather data could not be used due to the following reasons;

1. The magnitude and frequency of rainfall events was still not satisfactory at a daily time step.
2. It was observed that the global data does not in fact cover the baseline period as it starts from the year 1979, which is clearly after the baseline period in this study.

Resolving limitations in Climatic data

1. It was resolved that it is better to use the actual monthly climatic data collected from ZMD since the record was long enough.
2. That since the records in hydrological and climatic data were long enough, the analysis would be based on actual data to reduce uncertainties as opposed to using the modelling approach (since some input data were lacking).
3. All the computations requiring the use of climatic data were only carried out at annual (hydrological year) and or at a monthly time step. Further, they were only conducted for the period for which climatic data overlaps the hydrological data (1970-2006).
4. All the hydrological analyses that did not require the input of climatic data, for example FDC analysis and some time series analyses were done from the time of the start of records at each station (1955-2006 for Ngwerere and 1968-2006 for Chongwe 5025).

4.3 Methods

4.3.1 Introduction

This section briefly discusses the methods that were used to achieve each objective. It starts with the methods that were used to analyse the long term variation in climatic and hydrological time series data and how the data was finally divided in to the baseline and the post impact periods. It then gives the methods that were used to analyse the changes in runoff yield (runoff coefficients). Lastly but not the least, the section discusses how the impacts of land use change on dry and wet season flows were assessed.

4.3.2 Long term variation in Rainfall, Temperature and Runoff

Simple linear trend lines and moving averages were used to examine the temporal variation of climatic and hydrological data. Further, Double Mass Curves and the Petititi test were used to determine the year(s) in which abrupt changes in discharge records began in the study area. All these would help to better interpret how different factors might have affected the hydrologic regime. The outputs are in form of graphs and tables. The change point detection procedure is further reviewed below.

4.3.3 Change-point analysis

To estimate when humans began causing significant changes on the flow regime, change point analysis is used by researchers. Among the several techniques used, this study adopted the Double Mass Curves Analysis and the non-parametric Pettitti (1979) test to detect change-points in the climatic and hydrological time series.

The Double Mass Curve method has been used by several scholars such as Gao et al. (2011); Pena Arancibia et al. (2012); Wagesho (2014) to detect the time of change in streamflow. The changes are identified by the breaks or major bends in the graph of cumulative rainfall vs cumulative streamflow. The assumption behind this technique is that the relationship between rainfall and runoff will remain the same (straight line) unless there is a change in the catchment characteristics. Therefore, a break, or change in the graph (line) is assumed to be due to humans (land use). Double Mass Curves can also be made by plotting time (year on x-axis) vs cumulative rainfall (y-axis). The Double Mass Curve method is enough on its own in terms of showing change points. But one can also use a statistical test such as the Pettiti test, Mann Kendall test and others to test the significance of the breaks observed on the Double Mass Curve. In this study, the Pettiti test method is adopted for the said purpose.

Pettitt test

Thus, the second method used for change detection in this study is the Pettitti test. The Pettitt test method is able to detect a significant change in the mean of a time series if the exact time of the change is unknown just like was the case in this study.

Given that X_1, X_2, X_3,…, X_T is a time series of a variable, where T is the length of the time series. The null hypothesis is that there is no change in the mean, while the alternative hypothesis is that there is a change in the mean of the time series at time‘t’. This means that the values (X_1, X_2,…,X_t) have a common distribution function of F_1 (X). On the other hand, the values (X_{t+1}, Xt_{+2},…,X_T) also have their own common distribution function F_2 (X). Therefore; $F_1 (X) \neq F_2 (X)$.

Hence, the test statistic is defined by;

$$K_T = Max_{(1 \leq t \leq T)} \left| U_{t,T} \right|, \tag{4.4}$$

Where $U_{t,T}$ is a version of Mann-Whitney statistic that tests whether two samples (X_1, X_2,…X_t) and (X_{t+1},X_{t+2},…X_T) are from the same population. This test is given by,

$$U_{t,T} = \sum_{i=1}^{t} \sum_{j=t+1}^{T} \text{sgn}\left(X_t - X_j\right), \tag{4.5}$$

And

$$\begin{aligned} &\text{if}\left(X_t - X_j\right) > 0, \quad \text{sgn}\left(X_t - X_j\right) = 1 \\ &\text{if}\left(X_t - X_j\right) = 0, \quad \text{sgn}\left(X_t - X_j\right) = 0 \\ &\text{if}\left(X_t - X_j\right) < 0, \quad \text{sgn}\left(X_t - X_j\right) = -1 \end{aligned} \tag{4.6}$$

The p value associated with K_T is approximated by;

$$\rho = \exp\left(\frac{-6K_T^2}{T^3 + T^2}\right). \tag{4.6}$$

Hence, choosing a significance level of α = 0.10 in this study, the null hypothesis of no change is rejected and the alternative hypothesis is acceptable if the p value is less than alpha (α). Where a change exists, the test partitions the time series at the location of change in to two sub series. There are no specific assumptions or restrictions for the Pettitt test, except that data must be continuous.

4.3.4 Runoff coefficients

In order to analyse the runoff yield in different windows representing varying land use, Runoff coefficients were used. Zhang et al. (2007) have observed that Runoff coefficients are an important index that reflects the runoff yield.

A Runoff coefficient is simply a dimensionless ratio of the volume of runoff in a given time period to the volume of precipitation over the watershed in the same time period. They can be computed at different time steps such as event, day, monthly or annual provided flow data and the corresponding precipitation data are available. Researchers have used different terminologies to refer to the parameter called Runoff Coefficient. As observed by Blume et al. (2010), some researchers have called it Response factor, hydrologic response, runoff ratio, Q:P ratio, Qrec/P, water yield, water budget, water balance, conversion efficiency and so on.

Theoretically, Runoff coefficients range from 0 to 1.0 and are influenced by geology, topography, soils, rainfall intensities and land use, mainly perviousness and vegetation cover (Vandegrift and Stefan, 2010). RCs can thus reflect how the runoff potential has changed following a change in land use. Consequently, they have been used by several researchers (including Rose and Peters, 2001; Zhang et al., 2007; Lenhart et al., 2011a) to study the effects of changes in land use on streamflow.

In this study, annual runoff coefficients were computed for each period and for the entire period of study. They were computed based on the hydrological year which is from October to September in Zambia and not on the basis of the calendar year. Additionally, monthly runoff coefficients were computed and compared in each period. Runoff coefficients were computed based on the concept of Rational Method;

$$Q = F.C.I.A, \tag{4.7}$$

where, Q is Peak runoff in [m^3/s]; C is Runoff coefficient [-], I is Rainfall intensity in [mm/hr], and A is the Catchment area in km^2 and F is simply the conversion factor to convert discharge to m^3/s.

Runoff was converted from m^3/s to depth (mm) using the area covered by each hydrological station and time. Hence, the final expression used to compute runoff coefficients was;

$$Runoff\ coefficient\ (dimensionless) = \frac{Runoff(mm)}{Rainfall\ (mm)}. \tag{4.8}$$

4.3.5 Analysis of flow regimes (Mean Monthly flow)

Graphs of mean monthly flows were prepared and compared in each period. This was done in order to understand the changes that have occurred within the annual cycle (in different seasons). This would give the changes in wet season and dry season flows. This monthly analysis was complemented by Flow Duration Curve analysis (on a daily time step). The Flow Duration Curve analysis is discussed below.

4.3.6 Flow Duration Curve analysis

Flow Duration Curves show the relationship between the magnitude and the percentage of time that the discharge was equalled or exceeded in the period of measurement. They give a simple but comprehensive graphical view of the overall historical variability of streamflow. The shape of the flow duration curve is determined by the rainfall pattern, catchment size, and physiographic characteristics of the catchment, water resources development and land-use type (Smakhtin, 1999; Zhang et al., 2012). The FDC approach provides a statistical method for describing various streamflow regimes and thus allows for identification of differences in streamflow time series (Smakhtin, 2001; Zhang et al., 2012). Flow duration curves can be constructed at various times steps for example daily, weekly, or even on monthly streamflow.

FDCs were constructed on daily streamflow. This was done by ranking the daily streamflow data from the largest to the smallest. Then assigning each discharge value a rank (M), starting with 1 for the largest daily discharge value. Thereafter, computing the percentage of time each flow is equalled or exceeded using the equation below.

Exceedence probability (P):

$$P = 100 * \left(\frac{M}{n+1}\right), \quad (4.9)$$

where P is a probability that a given flow will be equalled or exceeded (% of time). M is the ranked position on the listing (dimensionless). n = number of events for the period (dimensionless).

The FDC graph was then obtained by plotting each flow against the percentage of time it is equalled or exceeded. Results are presented in graphs and table (flow indices).

5. RESULTS

5.1 Introduction

This chapter presents the results of the study. The chapter is divided in to three sections according to objectives. The first section thus gives the results of the long term variations in climatic and hydrological data. The second section gives the changes that have occurred in runoff generation (runoff yield). This is given by the changes in Runoff Coefficients. Lastly but not the least, the chapter presents the changes that have occurred to dry and wet season flows. This is given using the graphs of mean monthly flow and FDCs (thus both daily annual FDCs and daily periodic FDCs are used).

5.2 Long term variation in Climatic and Hydrological time series data

The first part of this section gives the general trend in climatic and stream flow data in the catchment. The second part of the section identifies the beginning of change in hydro-meteorological data.

5.2.1 General variation in Rainfall, Temperature and Runoff

In general, rainfall shows a decrease while temperature shows an increase. Unexpectedly runoff shows an increase in general. Details are briefly discussed below.

Rainfall

In general, rainfall in the catchment shows a decreasing trend over the period from 1970 – 2006 (Figure 5.1 *top left*). The five year moving average of rainfall is given in Appendix 1.

Applying the Pettitti test on the rainfall time series data from 1970-2006 shows that a weak downward trend in rainfall started in the hydrological year 1981/82, with a p value of 0.087 at 10 % significance level (Figure 5.3 *top right*).

The average before change in rainfall (that is; in the period from 1970/71 to 1981/82) was about 935 mm/year and about 773 mm/year after change (1982/83 to 2005/06). The long term average rainfall (Appendix 2) from 1970 to 2006 is about 827.3 mm/year. The relationship between rainfall and runoff is given in Appendix 3.

Temperature

Temperature shows an increasing trend in the study period (Figure 5.1 *top right*). Application of the Petitti test on the temperature time series over the period from 1970-2006 showed that a strong increasing trend in temperature started in the hydrological year 1985/86 with $p = < 0.0001$ (graph in Appendix 4).

The long term mean annual temperature from 1970 to 2006 is 20.78 ^{O}C. The relationship between temperature and runoff is given in Appendix 5.

Runoff

In order to better understand the streamflow trends in Chongwe upper catchment, runoff was analysed at Ngwerere weir and Chongwe 5025 from the start of records at each station. The records at Ngwerere weir are much longer since they date back to as early as 1955. Hence flows at this weir are better in terms of approximating the baseline conditions (period with less human impact) than those at Chongwe 5025 where the records start in 1968.

The results indicated a general increase in runoff despite a reduction in rainfall and increase in temperature. The increase in runoff was larger at Ngwerere weir (Figure 5.1 *bottom left*) which is affected by urbanisation, and does not have major water abstractions upstream, and has a longer period of record.

The long term variation in flows at Chongwe 5025 shows a slightly downward slope, which could also be indicative of increased water abstraction in the area (Figure 5.1 *bottom right*).

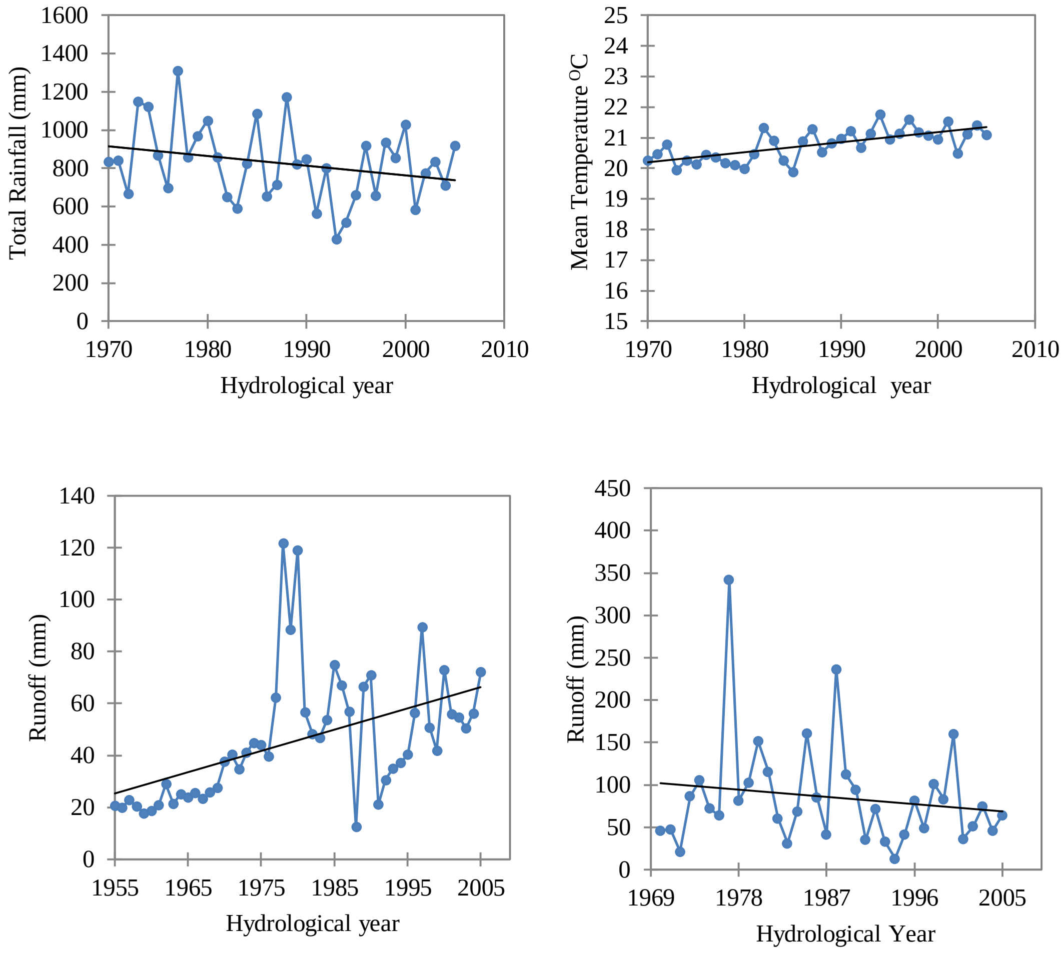


Figure 5.1: Long term variation of Rainfall (top left), temperature (top right) and Runoff at Ngwerere Weir (bottom left) and Chongwe 5025 (bottom right) in Chongwe.

5.2.3 Beginning of dramatic change in streamflow and selection of the Baseline Period

Double Mass Curve Analysis

Double Mass Curve Analysis shows that major changes in stream flow occurred in two periods (Figure 5.2). The first major change occurred in 1976-77. The causes of this change are not known. Probably it was due to floods in the period from 1977 to 1981, in interaction with land use. Another significant change in stream flow was observed in the water year 1990-91. The results of Double Mass Curves were complimented by the Pettiti test, whose results are presented below.

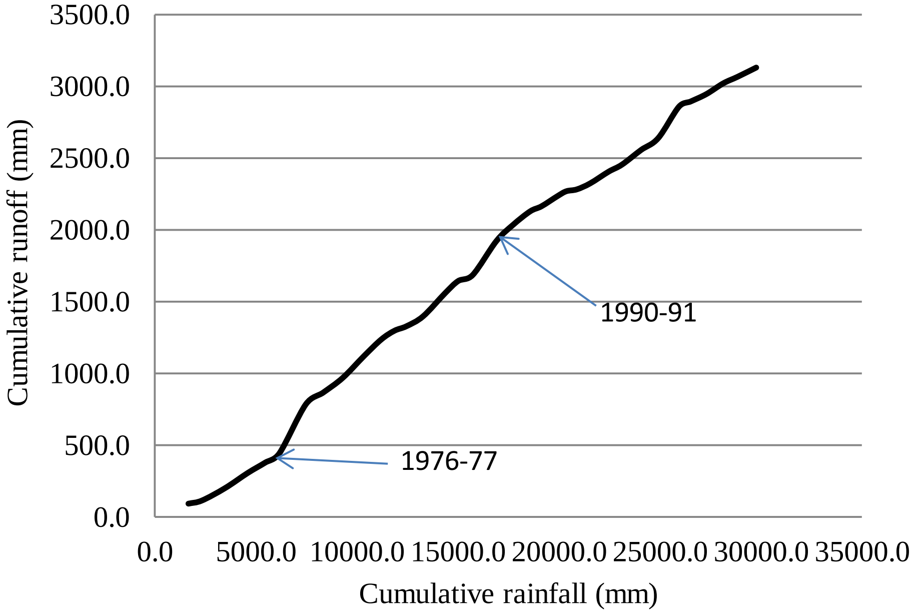


Figure 5.2: Double Mass Curve of time of abrupt changes in streamflow

The Pettitti test method

Further analysis involved applying the Pettiti test to the stream flow time series data. This was done in order to test the significance of the streamflow changes in 1976-77 and 1990-91 as identified by the double Mass Curve analysis. The null hypothesis for the Pettitt test was that data are homogenous and the alternative hypothesis was that there is a date at which there is a change in the data.

At Ngwerere weir, the Pettitti test detected the hydrological year 1972/1973 as the year when significant change (upward shift) occurred with $p < 0.0001$ at the significance level of 1 % (Figure 5.3 *top left*).

At Chongwe 5025 the test confirmed a change occurred in the year 1990-91 (Figure 5.3 *bottom right*). However, the change was not statistically significant (p value = 0.225). Worse still was the change in 1976-77, that had a higher p = value of 0.296 at Chongwe 5025 (Figure 5.3 *bottom left*). The non-significant changes at Chongwe 5025 could be because humans were almost beginning to significantly affect the flow regime by the time the Chongwe 5025 station was opened around 1968. This can be seen by the flows at Ngwerere weir where the flow records are longer (they start from 1955). In this regard, the flow record at Ngwerere weir provides a better picture of the baseline and present conditions.

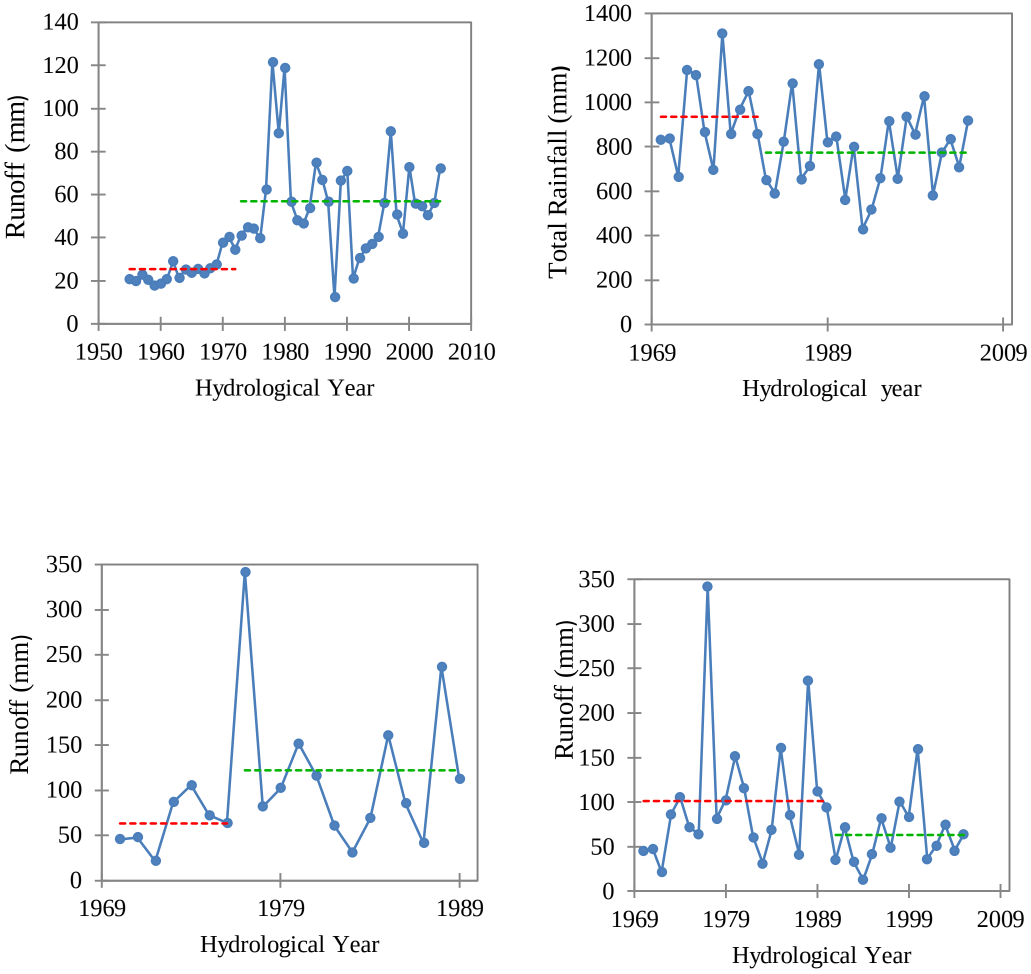


Figure 5.3: Beginning of Change in; Runoff at Ngwerere weir (top left) and Chongwe 5025 (bottom right in 1991/92 and bottom left in 1976/77) and Rainfall (top right)

Hence, following Double Mass Curve analysis and the Pettiti test results, three windows or study periods were chosen for this study as follows;

1. Baseline period (before 1976) to represent the period with less human impacts on the hydrologic regime.
2. After change period one (from 1979 to 1989) to represent the period when significant human impacts were beginning to appear on the hydrologic regime, but also when climate had a major impact.
3. After change period two (from 1990 to 2006) to represent the recent period with significant human impacts on the hydrologic regime.

   The above periods are shown pictorially in Figure 5.4.

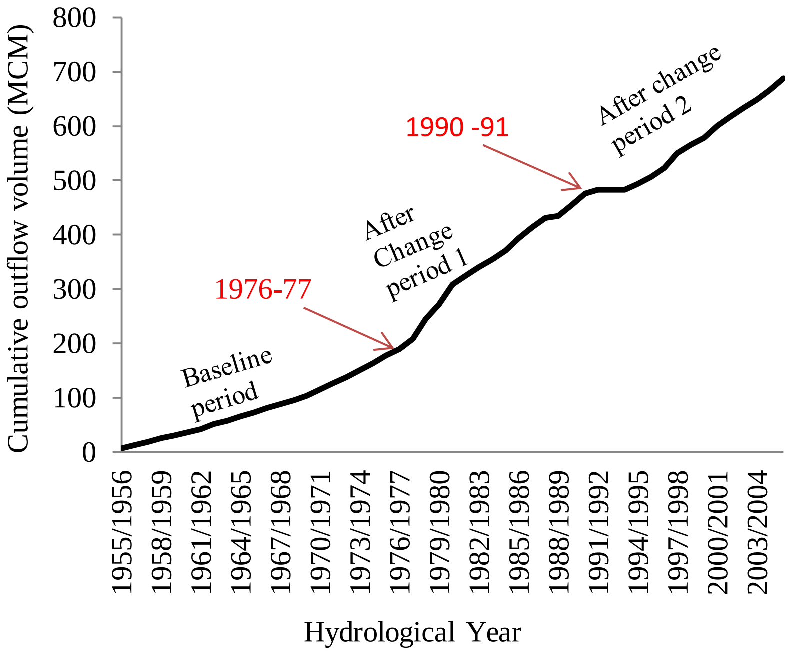


Figure 5.4: Selected windows representing various levels of human impact on streamflow

Table 5.1 summarises the rainfall, temperature and streamflow (runoff) amounts in the three windows at Ngwerere weir and at Chongwe 5025. The total annual runoff has increased by about 36 % and 8 % at Ngwerere and Chongwe bridge station respectively. This is despite precipitation decreasing by about 14.7 %. This highlights the impact of reduced infiltration rates in increasing the total runoff.

Table 5.1: Change in total Hydrological year Rainfall, Temperature and Runoff from 1970-2006 in Chongwe upper catchment

	Rainfall (mm)	Temperature ^{O}C	Ngwerere Runoff (Million cubic meter)	Chongwe bridge Runoff (Million cubic meter)
Baseline (pre 1976)	882.29	20.33	12.23	113.94
Post Impact (1990-2006)	752.44	21.14	16.62	123.14
Absolute Change	-129.85	+ 0.81	+ 4.39	+ 9.2
% Change	-14.72	+ 4	+ 35.9	+ 8.07

5.3.0 Changes in water yield - Runoff Coefficients

Runoff coefficients provide information about the runoff generation potential of a catchment. Hence Annual RCs are used in this study, supplemented by Monthly RCs.

5.3.1 Changes in Runoff generation: Annual runoff coefficients

In order to understand how runoff generation has changed in Chongwe catchment over time, annual (hydrological year) runoff coefficients were computed for the period from 1970 to 2006. Figure 5.5 and 5.6 indicate the long term variation in runoff coefficients at Ngwerere weir and Chongwe 5025 respectively.

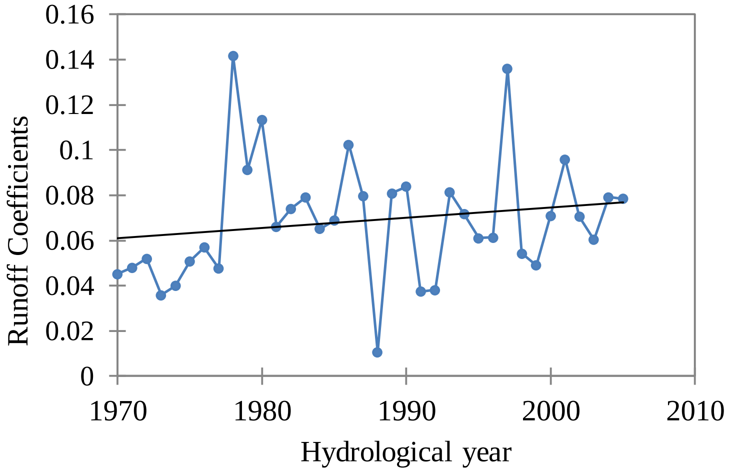


Figure 5.5: Annual Runoff Coefficients at Ngwerere weir

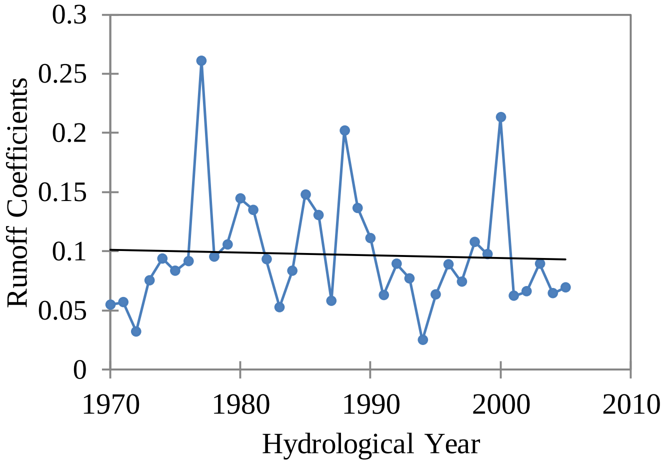


Figure 5.6: Annual Runoff Coefficients at Chongwe 5025

The mean annual (hydrological year) runoff coefficients were compared for the three windows (pre 1976, 1979-1989, 1990-2006). Despite the decreasing rainfall amounts (as shown in table 5.1), runoff coefficients have increased by about 40 % and 28.6 % at Ngwerere weir and Chongwe 5025 respectively (Table 5.2).

Table 5.2: Mean Hydrological year Runoff Coefficients in Chongwe Upper Catchment

Station	Pre 1976	1979-1989	1990-2006	Entire Study Period	% Change
				Average from 1970 to 2005	(1992-2006) minus (1970-1978)
Ngwerere (5016)	0.05	0.08	0.07	0.06	40
Chongwe (5025)	0.07	0.12	0.09	0.09	28.6

In the absence of human factors, one would expect a subsequent decrease in runoff coefficients due to a decrease in precipitation. The increase in runoff coefficients despite a decrease in precipitation shows that the catchment now experiences more runoff from less precipitation.

This trend highlights the impact of land use change mainly through increase in imperviousness in the catchment. It is therefore not surprising that Ngwerere tributary has shown a bigger change in runoff coefficients (40 %) compared to Chongwe Bridge on the main Chongwe River (28.6%). The Ngwerere is located in an urbanised (Lusaka City) area; hence the weir at Ngwerere captures storm runoff that enters the Ngwerere from the urban Lusaka.

Due to water abstraction (dams) downstream the Ngwerere weir, some of the storm water generated from urban Lusaka may not reach the Chongwe 5025 (regarded as the outlet is this study).

Thus, the lower runoff coefficients at Chongwe 5025 could be due to increased water abstraction (especially by dams) upstream the Chongwe 5025. There are several earth dams (< 1km^2) including the Rays dams (8 km^2) all of which are above the Chongwe 5025 station. Further, Chongwe 5025 station covers a much bigger area and thus has higher diversity of land use, geology and topography which might have some effects on the spatial distribution of rainfall. Nevertheless, it is still surprising that despite the increased water abstraction through dams in recent years, coupled with the decreasing precipitation and increasing temperature trends, runoff and runoff generation are higher compared to the baseline conditions at Chongwe 5025. Reduced infiltration rates could explain this.

5.3.2 Monthly runoff coefficients

The results reveal an increase in runoff coefficients for all the wet months. Thus, the baseline period has the lowest runoff coefficients. Appendix 6 and 7 show the monthly runoff coefficients in the three windows at Ngwerere (5016) and Chongwe 5025 hydrological stations respectively.

It has also been observed that the monthly runoff coefficients are higher at the beginning of the hydrological year in October. This could be due to the rain season that is preceded by a dry and hot season (especially in September and October). Consequently, the ground is hard resulting into less infiltration and more surface runoff at the beginning of the hydrological year. But as the ground gets softer in November, infiltration rates increase resulting in less runoff coefficients during this period. However, runoff coefficients begin to rise again due to runoff memory from the preceding wet months. This explains why runoff coefficients are highest at the end of the rain season in April in all the three windows; despite the month of April having far less rainfall compared to the preceding months (November to March).

5.4.0 Changes in dry and wet season flows

This section presents the changes that have occurred within the annual cycle with respect to wet season (peak) flows and dry season (low) flows. The results are given through the monthly flow regimes and through FDCs. Below are the results.

5.4.1 Mean monthly streamflow (flow regimes)

The results indicate a shift in the time of peak flow at Ngwerere weir from February to January (Figure 5.7). Further, the entire range of flows (including peak flow and dry season flows) has increased. These changes reflect the impact of land use change on the hydrologic regime of Ngwerere. Urbanisation upstream the Ngwerere weir can largely be held responsible for these changes. This is because rainfall peaks still occur in January and the rainfall amount (peak) has in fact reduced (Figure 5.9).

At Chongwe 5025, the results indicate an increase in wet season flows (peak flow) and a reduction in dry season flows (low flows) (Figure 5.8). The results further confirm an increase in runoff volume (area under each graph). Unlike at Ngwerere, there is no change in the time of peak flow at a monthly time step at Chongwe 5025.

5.4.2 Mean Monthly rainfall

Changes in mean monthly rainfall are included here in order to understand the possible causes of the changes observed in mean monthly flows given above.

On average, the time of peak in monthly rainfall has not changed in all the periods (Figure 5.9). It has remained in January. Further, the analysis indicates that rainfall amounts and peaks have reduced. This clearly shows that the shift in the time of peak flow at Ngwerere weir, along with the increase in peak flow at both Ngwerere weir and Chongwe 5025 cannot be clearly explained by rainfall. Hence, land use changes in the area can largely be held responsible for the observed changes in the flow regime.

Analysis of mean monthly rainfall further shows that there is a time lag of one month at Chongwe 5025, since the time of peak in rainfall is in January while peak discharge at Chongwe 5025 is in February. However, at the urbanised Ngwerere; this time lag has diminished in the recent period (post 1990s).

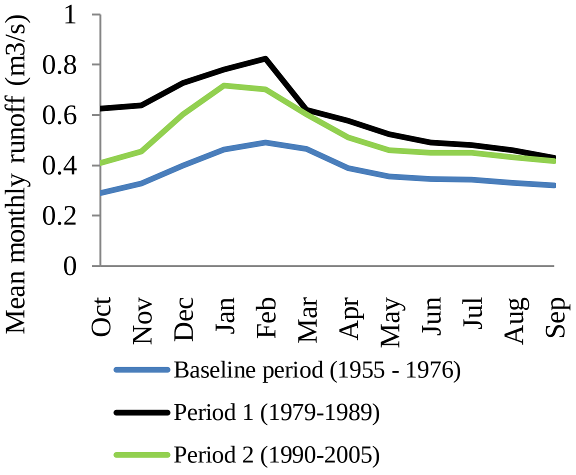


Figure 5.7: Average monthly runoff for different periods at Ngwerere weir

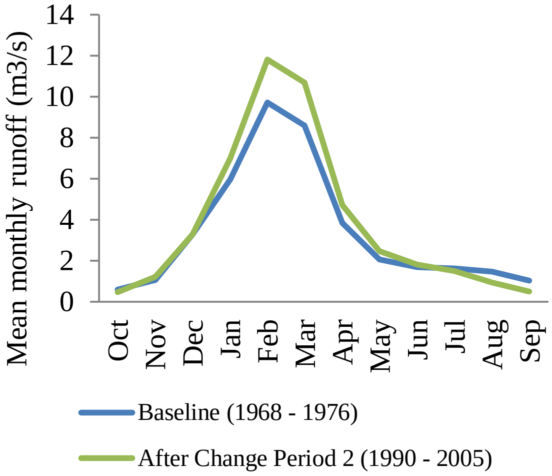


Figure 5.8: Average monthly runoff for different periods at Chongwe 5025

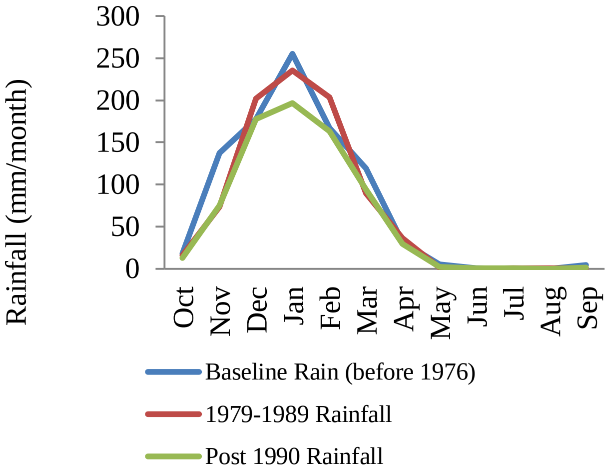


Figure 5.9: Monthly rainfall distribution in different periods

5.4.3 Flow Duration Curve (FDC) Analysis

This study takes high flows to be those exceeded from 1 to 25 percent of the time (Q_1 to Q_{25}) while low flows are those exceeded from 70 to 99 % percent of the time (Q_{70} to Q_{99}) as adopted from Brown et al, 2005 and Yao et al 2011. Both daily annual FDCs and daily periodic FDCs were used to analyse changes in the flow regimes.

Comparison of the flow regime based on Daily Annual FDCs

Brown et al, 2005 suggested using daily annual FDCs to minimise the impact of climate variability. Such FDCs are developed from daily flows within single years with similar rainfall amounts, but each year represents the period of interest where it is drawn from. Taking this in to consideration; FDCs were developed for 6 different years with similar rainfall.

At Ngwerere weir (Figure 5.10), the results of daily annual FDCs show increase in all aspects of the flow regime in recent years compared to years in the baseline (years before 1976) . This could be due to reduction in infiltration capacity and increase in waste water discharge in to the stream by the Lusaka urban communities as the City has grown in recent years. Appendix 8 gives the flow indices with their corresponding discharge values for each of these FDCs.

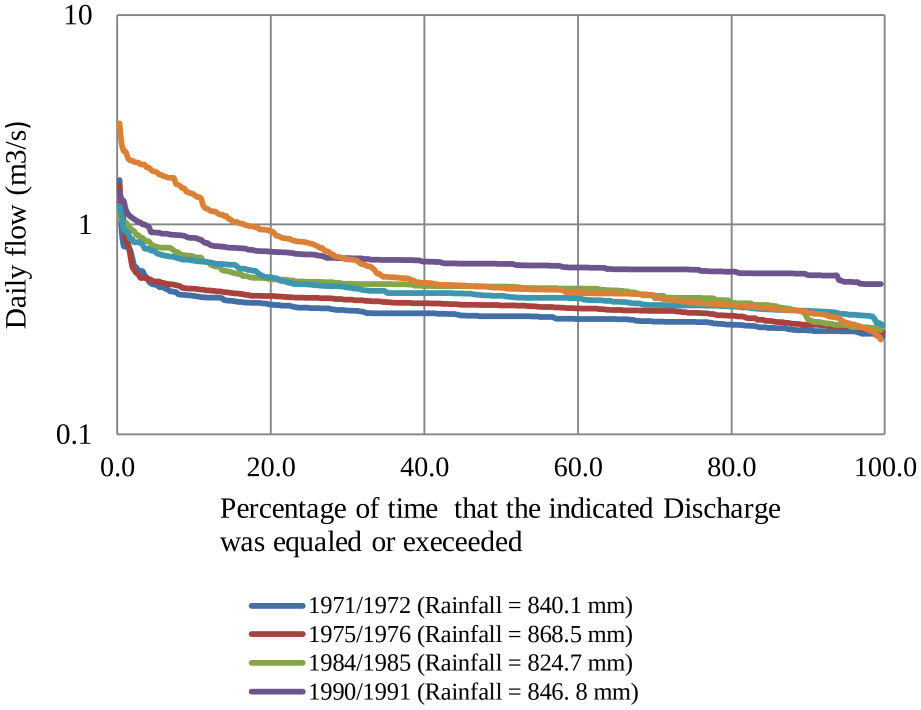


Figure 5.10: Annual FDCs at Ngwerere in years with similar rainfall

At Chongwe 5025, the peak flows have increased while low flows have reduced (Figure 5.11). The flow indices are given in Appendix 9. This highlights reduced infiltration opportunities in the catchment.

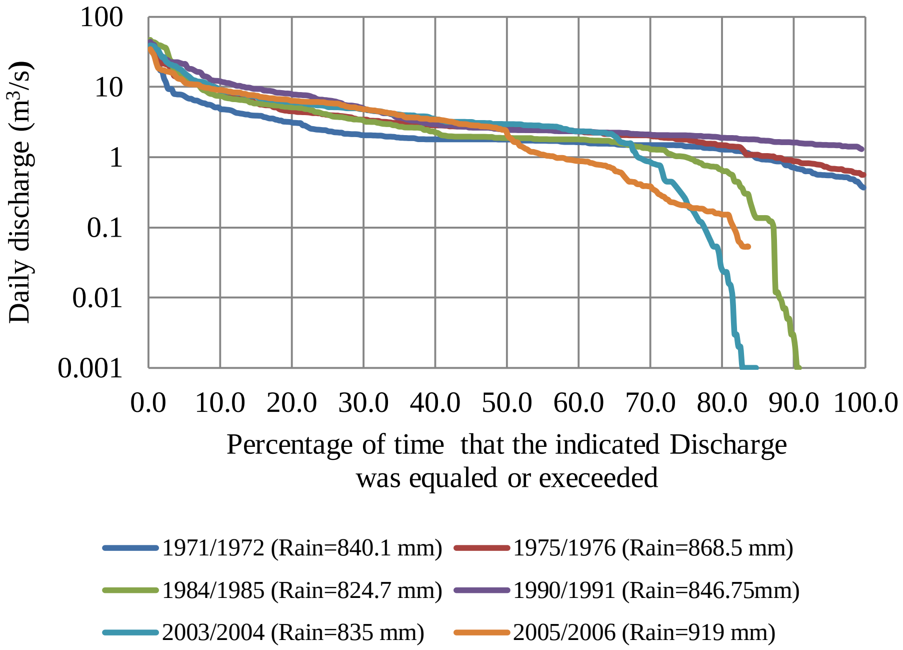


Figure 5.11: Annual FDCs at Chongwe 5025 in years with similar rainfall

Comparison of the flow regime based on Daily Periodic FDCs

Daily periodic FDCs have also been effectively used by several scholars to assess the impact of land use change on the flow regime (for example, Kaishaigili, 2008; Yao et al., 2011; Molina et al., 2012 among others).

Unlike daily annual FDCs that summarise the flow regime within single years with similar precipitation, daily period FDCs summarise the flows within periods of interest (within land use windows in this case). Daily periodic FDCs are thus made from daily flows in each land use window (study period).

The results of daily periodic FDCs were consistent with those of daily annual FDCs given above.

Thus, at Ngwerere estates weir, FDC (Figure 5.12 and Table 5.3) shows that the peak, for example flow Q_5 has increased by almost 80% while the low flow Q_{95} has increased by 5%.

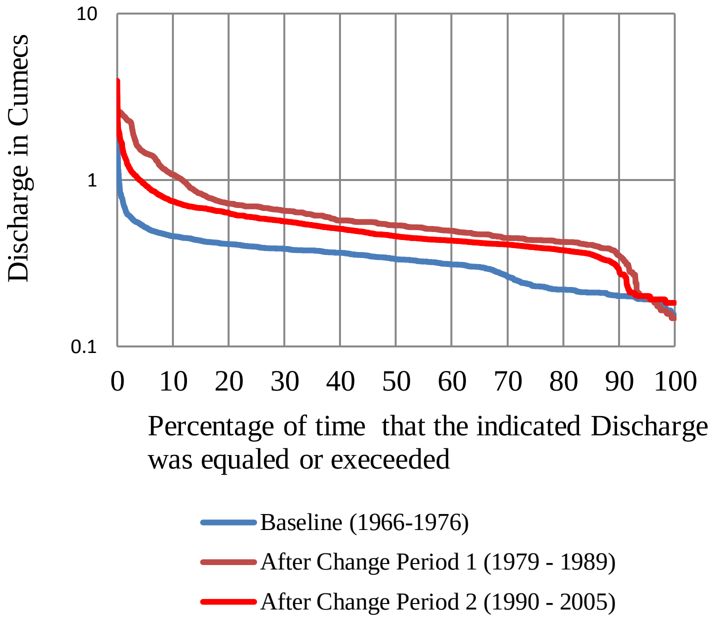


Figure 5.12: Changes in FDCs in the three windows at Ngwerere weir

Table 5.3: Flow indices and their associated discharges in different periods at Ngwerere weir *(extracted from daily periodic FDCs in figure 5.12)*

Flow indices	Baseline (1966-1976) (Discharge (m^3/s)	Period 1 (1979-1989) (Discharge (m^3/s)	Period 2 (1990-2005) (Discharge (m^3/s)	% Change (Baseline - period 2) (Discharge (m^3/s)
Q95	0.192	0.201	0.201	4.69
Q90	0.201	0.352	0.288	43.28
Q75	0.23	0.436	0.394	71.30
Q50	0.336	0.534	0.46	36.90
Q25	0.398	0.695	0.594	49.25
Q10	0.46	1.08	0.746	62.17
Q5	0.521	1.455	0.936	79.65

At Chongwe 5025, FDCs show that the peak flow, for example Q_5, has increased by about 31% while the low flow Q_{95} has decreased by 100% (Figure 5.13 and Table 5.4) when the present (1990-2006) discharges are compared to the baseline discharges.

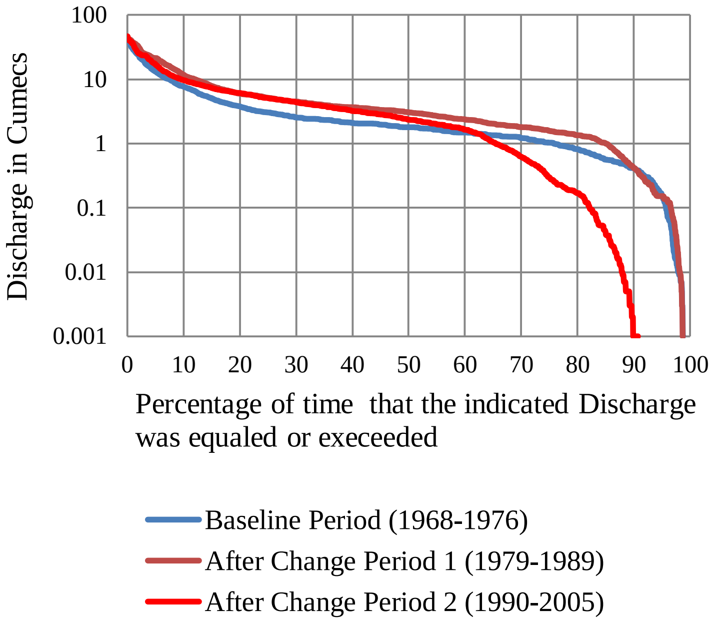


Figure 5.13: Changes in FDCs in the three windows at Chongwe 5025

Table 5.4: Flow indices and their associated discharges in different periods at Chongwe 5025*(extracted from daily periodic FDCs in figure 5.13)*

Flow indices	Baseline (Pre 1976) (Discharge (m^3/s)	Period 1 (1979-1989) (Discharge (m^3/s)	Period 2 (1990-2005) (Discharge (m^3/s)	% Change (Baseline - period 2) (Discharge (m^3/s)
Q95	0.152	0.152	0.000	-100.00
Q90	0.415	0.415	0.001	-99.76
Q75	1.032	1.577	0.297	-71.22
Q50	1.793	3.068	2.339	30.45
Q25	3.054	5.150	5.110	67.32
Q10	7.687	11.790	9.708	26.29
Q5	13.196	21.411	17.307	31.153

6. DISCUSSION

6.1 Introduction

This chapter discusses the results of the study and compares the observed results with the literature. Implications of the observed results are also briefly discussed under this chapter.

6.2 Long term variation in Climatic and Hydrological data

This section briefly discusses the observed long term variation in Climatic and Hydrological data

6.2.1 Decreasing rainfall and increasing temperature

Rainfall in Chongwe catchment as averaged at Kenneth Kaunda International Airport and Lusaka City Airport has shown a decreasing trend over the period from 1970 to 2006. The baseline period had an average rainfall of 882.29 mm per year while the post impact period had an average rainfall of 752.44 mm per year. This represents a rainfall decrease of about 129.85 mm or 14.7 % between the two periods. The general decreasing rainfall trends in Chongwe catchment are consistent with those obtaining across Zambia. Thus, in the National Adaptation Programme of Action (NAPA), MTENR (2007) have shown a general decrease in precipitation in all the three ecological regions of Zambia.

On the other hand, temperature in Chongwe catchment shows a general increasing trend. The increase in temperature is also consistent with MTENR (2007) who report a general increasing temperature trend in the country. In this study, temperature increased from 20.33 ^{o}C in the baseline period to 21.14 ^{o}C in the post impact period. This represents an increase in temperature of about 4 %.

6.2.2 Increase in Runoff

At Ngwerere weir, annual runoff has increased from the start of records in 1955. There are no major water abstractions upstream the Ngwerere weir. Hence in the wake of reduced rainfall amounts and increasing temperature trends, the increase in runoff at Ngwerere clearly reflects the impact of urbanisation in Lusaka City area.

At Chongwe 5025, when the baseline flows (before 1976) are compared with the post impact period (from 1990-2006), there is an annual runoff increase of a paltry 8 %. The insignificant increase in annual runoff at Chongwe could be explained by the presence of many dams upstream the station, most of which have been built in the post impact period. Hence, in recent years, a lot of water is abstracted upstream before it reaches the gauge station (Chongwe 5025). Obviously, decreasing rainfall trends also contribute to reducing the flows. However, the impact of climate in reducing the flow seems to have been surpassed by the impacts of reduced infiltration in increasing the flow. Hence this has resulted in a net increase of runoff especially at Ngwerere weir which is not affected by major abstractions upstream.

Thus, reduced infiltration rates due to urbanisation and deforestation can largely be held responsible for the general increase in runoff in the Catchment. This is because rainfall has reduced in the catchment. These findings and conclusions are consistent with those of several other scholars. For example, Molina et al. (2012), in the Andean region of Ecuador found a reduction in precipitation and an increase in runoff. They concluded that since the direction of change in climatic and discharge data was opposite, increases in runoff were most likely a result of the removal of native forest in that region of Ecuador.

6.3 Increase in Runoff coefficients

The increasing runoff coefficients (Discharge:Precipitation ratios) show that runoff generation in Chongwe upper catchment has increased. This is therefore in agreement with the observed general increase in annual runoff discussed in the previous section.

At Chongwe 5025, runoff coefficients have increased by 28.6 %. This shows that the general decreasing rainfall amounts and increasing temperature trends have not effectively reduced runoff generation and streamflow in general. In other words, there is more runoff from less rainfall in the recent years than was the case before 1976. This is despite the increased number of dams upstream the Chongwe 5025 station.

Lenhart et al. (2011a) observed that an increase in runoff coefficients (Q:P ratios) without a concurrent increase in rainfall is indicative of changes in land use, drainage or water withdrawal. Therefore, the increase in runoff generation is most likely driven by increased urbanisation especially around the Ngwerere tributary in Lusaka city and the rampant deforestation in the catchment as a whole. For example;

compared to the baseline period, the post impact period shows that Ngwerere weir has the highest increases in both runoff coefficients and runoff at 40 % and 35.9 % respectively. Due to its location in the Lusaka city area, the Ngwerere receives a lot of storm runoff arising from reduced infiltration opportunities due to tarred roads, drainages, sewers, parking lots, roofs and other impervious surfaces.

These results (28 % and 40 % increase in runoff coefficients at Chongwe 5025 and Ngwerere 5016 respectively) are consistent with the findings of Sakeyo (2008). Thus Sakeyo (2008) found a 33 % increase in runoff coefficients (though he calls them Qrec/P ratios) in the nearby Chalimbana River; also in Chongwe catchment, since Chalimbana is a tributary of Chongwe River. Sakeyo (2008) attributed the increase in runoff generation to deforestation in the area.

Additionally, the results of this study are consistent with those observed by several scholars in other parts of Africa and the world at large. Though Zambia is in southern Africa, the findings of this study fit well into what has come to be known as the ‘Hydrological Sahelian Paradox’ (Descroix and Amogu, 2012) in the Sahel region of West Africa. That is, many scholars such as Descroix and Amogu (2012) and Descroix et al. (2013) have observed significant increases in runoff coefficients and a general increase in stream discharges of the Sahel region during the same period that rainfall has decreased. Descroix and Amogu (2012) thus explain that there is a general consensus in that particular area; that the observed phenomenon is due to land use change through decreasing infiltration and decreasing water holding capacity of the soil.

All these case studies cited above (that is Sakeyo, 2008; Molina et al., 2012; Descroix and Amogu, 2012; Descroix et al, 2013) support the conclusion that land use change can largely be held responsible for the increased runoff coefficients and runoff yield in Chongwe catchment.

6.4 Changes in wet and dry season flows (peak vs low flows)

The impact of land use in Chongwe upper catchment is further reflected in the time of peak flow or flooding. At both Ngwerere weir and Chongwe 5025, the peak flow used to occur in February of each year before the 1990s. But in the post 1990s, the heavily urbanised tributary of Ngwerere shows that the time of peak flow now occurs in January. This represents a one month shift at Ngwerere, while the time of peak flow at Chongwe 5025 has remained in February. In line with the observations at Ngwerere, several scholars have also observed shifts in the time of peak flow. For example Kashaigili (2008) in neighbouring Tanzania observed that the peak flow is in recent years attained in March while it used to be attained in April in the previous years in that region. Similarly, Descroix et al. (2013) has observed that the time of peak flow in the Sahel region now occurs 40 days earlier than it did just over 40 years ago.

Additionally, the analysis of the mean monthly flows and FDCs in the three time periods reveals a major increase in peak flows at both Ngwerere weir and Chongwe 5025. However, the two stations show differences again with regard to the dry season flows. Thus the dry season flows, for example Q_5 have increased by almost 5 % (from 0.192 m^3/s to 0.201 m^3/s) at Ngwerere weir while the same have declined by 100% (from 0.152 m3/s to 0.0 m3/s) at Chongwe 5025. Further, the urbanised Ngwerere has the biggest change in wet season (peak) flow amounting to almost 80 % increase (from 0.521 m3/s to 0.936 m3/s). But the same peak flow, Q_5 has only increased by 31 % from 13.196 m^3/s to 17.307 m^3/s at Chongwe 5025 station. The huge increase in wet season (peak) flows at Ngwerere weir can be explained by increased storm runoff from impervious surfaces in the rain season, including the continuous discharge of waste water that goes on even in the dry season, thus causing the observed small increase in dry season flow as well at Ngwerere weir. This is more so because the urban population in Lusaka has increased (Table 3.1), hence more waste water discharges in to the stream and more impervious surfaces. It is highly unlikely that the small increase in dry season flows that is due to waste water could reach the downstream station of Chongwe 5025. This is due to increase in water abstraction activities downstream the Ngwerere weir but upstream Chongwe 5025.

At Chongwe 5025, the increase in peak flows is smaller (31 %) compared to the one at Ngwerere (about 80 %). This is expected. Kashaigili (2008) did not find a significant increase in peak flows after land use changes (irrigation and deforestation) in Tanzania. In case of Chongwe 5025, many dams now exist upstream the station, most of which have been built in the post impact period. These dams could thus explain why there appears to be only a small increase in peak flow. Dams have an impact of reducing peak flows hence the observed phenomenon.

Where they are properly designed, dams can still reduce peak flows, but increase dry season flows. The increase in dry season flows due to dams is unlikely in Chongwe especially that Mucheleng'anga et al. (2002) laments about the poor design of dams in the area; which does not permit any flow releases in the dry season.

It is therefore not surprising that the results indicated a 100 % reduction in dry season flows (Q_{95}) at Chongwe 5025. These results are also consistent with the findings of several other scholars. For example, in Tanzania, Kashaigili (2008) observed a 100 % reduction in dry season flows of Q_{95} from 2.85 m^3/s in baseline period to 0.0 m^3/s in the post impact period (with irrigation and deforestation).

It is worth noting that the impacts of deforestation on dry season flow will vary from region to region. Elsewhere, scholars such as Molina et al. (2012) observed an increase in dry season flows of Q_{90} and Q_{75} after deforestation, while at Chongwe 5025 in this study, all these flows have decreased significantly. Molina et al. (2012) attributed the increase in base flow to reduced evapotranspiration losses following the removal of native forest, and their (native forest) subsequent replacement by grass and crops. This is another example regarding the conflicting evidence on the impact of forest cover change on dry season flows. Bruijnzeel (1990) has clarified the conflicting evidence when he explains that it all depends on the net effect of changes in infiltration opportunities (including water storage capacity of the soil) and evapotranspiration of the respective land use types. In this regard, Bruijnzeel (1990) explains that if infiltration opportunities after deforestation fall to the point that the increase in volumes of storm flow surpass the increase in base flow associated with reduced evapotranspiration, then dry season flow will decrease and vice versa.

Arising from the foregoing, it can be said that; although reduced evapotranspiration in Chongwe catchment could have increased base flow, the net effect has been reduction in base flow (dry season flows) due to reduced infiltration along with reduced water holding capacity of the soil following land use changes (urbanisation, deforestation and soil degradation in cleared lands and in abandoned agricultural lands).

6.5 Implications for management

It is clear that runoff generation and streamflow in general in Chongwe upper catchment are higher than they were before the 1970s. However, caution should be exercised here especially during water resource allocation. This is because not all facets of the flow regime have increased. The excess runoff has only occurred in the wet season flows, and there is a huge reduction in the dry season flows. In view of the declining rainfall and increasing temperature trends in the area, there is certainly a reasonable justification to harvest the excess runoff in the wet season through dams. However, the dams must be properly designed to release some certain amounts of flows in the dry season in order to cover for the deficit in dry season flows. Releasing some water in the dry season could benefit downstream water users including the low flow dependent aquatic fauna and flora. This would contribute to efforts in reducing tensions between upstream (mainly commercial farmers) and downstream water users (mainly indigenous people) in the catchment.

Monitoring and a legal framework would be a pre requisite for this to work, since some dam owners or operators could be unwilling to release some flows especially in drought years. The results of this study are in full support of the clause on environmental flows in Zambia’s new water act; known as the Water Resources Management Act No. 21 of 2011 as amended.

7. SUMMARY AND CONCLUSIONS

Introduction

This chapter summarises the findings and conclusions on each objective. The overall conclusion of the thesis is also given. The chapter then goes on to give recommendations and suggestions for future research in the area. Finally limitations of the study are briefly discussed

a) Long term variation in climatic and hydrological time series in Chongwe upper catchment

In general, the results show that rainfall is decreasing, while temperature is increasing. Since there is no increase in rainfall and there is a rise in temperature, runoff is expected to decrease. Surprisingly, runoff is increasing (especially at Ngwerere) despite the aforementioned circumstances. This is despite increased water abstraction mainly through dams in recent years in the catchment. Therefore, since the changes in climatic data cannot explain the increase in runoff, land use change has been assumed to be the major driving force increasing surface runoff in the catchment. Thus, increased urbanisation (built up area) and reduction in forest cover (deforestation), soil degradation among others have reduced the infiltration rates in the catchment, which has in turn increased surface runoff generation and streamflow in general. There could also be some increase in runoff due to water gain from reduced interception and reduced evapotranspiration losses following deforestation.

b) Runoff coefficients before and after dramatic change in hydrologic data

The dimensionless runoff coefficients were computed as a ratio of runoff depth in millimetres to areal rainfall depth in millimetres.

Analysis of runoff coefficients shows an increasing trend at both Ngwerere weir and Chongwe 5025. When compared, the runoff coefficients in the post impact period (post 1990) are higher than those of the baseline period (before 1976). The biggest increase in runoff coefficients was observed at the urbanised tributary of Ngwerere. This is also the same station that showed a bigger increase in annual runoff. In other words, the runoff generation has increased in Chongwe upper catchment, despite the general decrease in rainfall. The increase in runoff coefficients shows that less rainfall is now producing more runoff. This is surprising and can most likely be explained by the role of land use change (especially urbanisation and deforestation) in reducing infiltration opportunities which in turn increase storm runoff.

c) Changes in Dry and Wet Season flow

Changes in the flow regimes were analysed in order to understand the changes that have occurred within the annual cycle.

At the urbanised Ngwerere, the results show an increase in both wet season (peak) flow and dry season (low) flow. As expected, the greatest increase is in peak flow. The time of peak flow (flood) has also shifted to occur one month earlier than it did before the 1990s at Ngwerere weir. These results reflect the role of increased imperviousness through drainages, parking lots, roofs and tarred roads in increasing storm runoff generation, and streamflow in general. The unexpected increase in dry season flows at Ngwerere is due to continuous discharge of waste water in to the stream by urban dwellers in Lusaka City.

At the downstream station of Chongwe 5025 (considered the outlet station of Upper Chongwe in this study), there has been an increase in peak flow, but a huge reduction in dry season flows (dry up). The probable explanation for the reduction in dry season flows is that; following the cutting of forest to pave way for other land use types, infiltration opportunities have decreased to the point that the increase in storm flow volumes is more than the increase in base flow resulting from reduced evapotranspiration. In other words, the base flow gained from reduced evapotranspiration in Chongwe catchment could be less than the base flow losses caused by reduced infiltration opportunities. The results confirm that there is more runoff in the wet season in the post impact period, but this wet season runoff is not sustained during the dry season; most likely due to reduced water holding capacity of the soil.

The thesis concludes that land use change can largely be held responsible for the increase in; runoff generation and in streamflow in general; increase in peak flow; shift in the time of peak flow at Ngwerere; maintenance of dry season flows at Ngwerere weir and at the same time reduction in dry season flows at Chongwe 5025.

RECOMMENDATIONS

1. This study recommends the use of environmental flows as a way of reducing the upstream and downstream water conflicts.
2. Alternative means of livelihood in the catchment are needed to reduce pressure on the remaining forest. Reforestation could also be encouraged.

FUTURE RESEARCH

1. Future research should investigate the impact of climate on the flow regime of Chongwe. (Climate might have also contributed to the decrease in dry season flows).
2. There is also need for future research to study the changes that have occurred on sedimentation rates and river geometry. This comes in the wake of increased peak flows observed in this study, deforestation and the reported chaotic sand mining in the catchment; all of which could have implications on the river sedimentation, which then affects both water quantity and quality.

LIMITATIONS OF THE STUDY

1. Climatic data was only available on a monthly time step and did not have the necessary information such as number of wet days needed in most weather generators to estimate the daily weather values. Additionally, other climatic data such as humidity, wind speed, solar radiation and so on were not available before the 1980s (thus, they were not available in the baseline period).
2. Specific land use data of the study area could not be found especially for the baseline period (before 1976).

GLOSSARY

Base flow – is the sustained low flow of a stream that enters the stream channel from groundwater sources.

Dry season flows – are taken be streamflow in Zambia's dry months (both in the cool and in the hot season) from May to October. The term is used interchangeably with ***low flows*** in this thesis.

Hydrological regime – It is the characteristic behaviour and total quantity of water in a drainage basin. In this study, hydrologic regime is a collective term referring to annual streamflow, wet and dry season flows.

Land use change –refers to the changes in the area covered by forest, water, as well as changes in other landscape components of urban/residential, commercial, agriculture, and so on.

Land use refers to the human uses of the landscape for residential, commercial, agricultural, etc. In this thesis, it can also be taken to mean the same as **Land cover**, which refers to the natural surface landscape components of forest, water, wetlands, urban, and so on.

Runoff – discharge expressed in units of depth (millimeters).

Runoff Coefficient – Refers to a dimensionless ratio of runoff (in millimetres) to areal rainfall (in millimetres).

Streamflow or (discharge/outflow/flow) – refers to the volume of water passing past a given point per unit time in the stream. Units used are m^3/s.

Wet season flows – are taken to be streamflow in Zambia's wet months (rainy season) from November to April. The term is used interchangeably with ***High (Peak) flows*** in this thesis.

Water Yield **-** Amount of water resulting from a unit area of a drainage basin per given time. Means the same as Runoff generation in this study.

REFERENCES

Bosch J.M., and Hewlett J.D., 1982: A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. Journal of Hydrology 55 (1/4), 3–23.

Brisbane Declaration., 2007: ‘’Environmental Flows are Essential for Freshwater. Ecosystem Health and Human Well-Being,’’ Declaration of the 10th International River symposium and International Environmental Flows Conference, held in Brisbane, Australia.

Brown A.E., Zhang L., McMahon T.A., Western A.W., and Vertessy R.A., 2005: A review of paired catchment studies for determining changes in water yield resulting from alterations in vegetation. Journal of Hydrology 310 (2005) 28–61.

Bruijnzeel L.A., 1990: Hydrology of moist tropical forests and effects of conversion: a state of knowledge review. UNESCO, International Hydrological Programme, Paris/Vrije Universiteit, Amsterdam, 224 pp.

Buytaert W., In˜iguez V, and Bie`vre, B.D., 2007: The effects of afforestation and cultivation on water yield in the Andean pa´ramo. Forest Ecology and Management, FORECO-10499; No of Pages 9

Buytaert W., De Bievre, B., Wyseure, G., Deckers, J., 2004: The use of the linear reservoir concept to quantify the impact of land use changes on the hydrology of catchments in the Ecuadorian Andes. Hydrol. Earth Syst. Sci. 8, 108–114.

Central Statistics Office., 2004: 2000 Census of Population and Housing. Lusaka Province Analytical Report. Volume 5. CSO, Lusaka, Zambia.

Central Statistics Office.,2012: Zambia 2010 census of population and housing, Population summary report, CSO, Lusaka, Zambia.

Chidumayo E. N., Masaileti I., Ntalasha H. and Kalumiana O. S. 2001: Charcoal potential in southern Africa (CHAPOSA) – report for Zambia. Stockholm Environment Institute, Stockholm.

Chidumayo E.N. 2009: Determining the non-renewable portion of biomass utilized in charcoal production for Lusaka. CDM Document. UNFCCC. Copenhagen, Denmark.

Chileshe P, Trottier. J, and Wilson. L., 2005: Translation of water rights and water management in Zambia, International workshop on 'African Water Laws: Plural Legislative Frameworks for Rural Water Management in Africa', 26-28 January 2005, Johannesburg, South Africa.

Chongwe District Council – CDC., 2006: Report on base line data for water consumption and and utilization, Prepared for d-washe. Report was accessed from: http://s3.amazonaws.com/zanran_storage/www.iclei.org/ . Accesed on 06/12/2013.

Chow, ven Te: Handbook of applied Hydrology, MacGraw-Hill, New York, 1964.

Cloud K. C.,2007: "Changes and trends in stream flow during floods and droughts in urbanizing Christina River Basin" (unpublished), Master's thesis published by Water Resources Agency, Institute for Public Administration, College of Human services, Education & Public Policy; U. of Delaware. "Stored: www.wr.udel.edu". Accessed on 4/02/2014.

Fahey B., Jackson, R., 1997: Hydrological impacts of converting native forests and grasslands to pine plantations, South Island, New Zealand. Agricultural and Forest Meteorology 84 (1–2), 69–82.

Forslund A. et al., 2009: Securing Water for Ecosystems and Human Well – being: The Importance of Environmental Flows. Swedish Water House Report 24. SIWI.

Gao P., Mu, X.M., Wang, F., and Li, L., 2011: Changes in streamflow and sediment discharge and the response to human activities in the middle reaches of the Yellow River. Hydrol. Earth Syst. Sci., 15, 1–10.

Geremew A.A., 2013: Assessing The Impacts of Land Use And Land Cover Change on Hydrology of Watershed: A Case Study on Gilgel–Abbay Watershed, Lake Tana Basin, Ethiopia (unpublished), Dissertation submitted in partial fulfilment of the requirements for the degree of Master of Science in Geospatial Technologies, Universidade Nova, Portugal, Universitate Jaume I, Spain and Westfälische Wilhelms-Universität Münster, German. "Stored: http://run.unl.pt/bitstream/10362/9208/1/TGEO0098.pdf ".

Hibbert A.R., 1967: Forest treatment effects on water yield. In: W.E. Sopper and H.W. Lull (Editors), Int. Symp. For. Hydrol., Pergamon, Oxford, 813 pp.

Ines A.V. M. and Hansen J.W., 2006: Bias correction of daily GCM rainfall for crop simulation studies, Agricultural and Forest Meteorology, Vol. 138, pp. 44-53.

Kashaigili J.J., 2008: Impacts of land-use and land-cover changes on flow regimes of the Usangu wetland and the Great Ruaha River, Tanzania. Elsevier Journal of Physics and Chemistry of the Earth 33:640-647.

Langford K.J.,1976: Change in yield of water following a bushfire in a forest of Eucalyptus regnans. J. Hydrol., 29: 87—114.

Lenhart C., Peterson, H., Nieber, J., 2011a: Increased Streamflow in Agricultural Watersheds of the Midwest: Implications for Management. Watershed Science Bulletin. CWP, Ellicott City, MD. Volume 2, Number 1. Pages25-31.

Lenhart C., Petersen, H., Titov, M. and Nieber, J. 2011b: Quantifying differential streamflow response of Minnesota ecoregions to climate change and implications for management. Report to the Minnesota Water Resources Center for USGS WRRI state program. March, 2011. Online at:http://water.usgs.gov/wrri. Accessed on 18/03/2014.

Liu J., Williams J.R., Wang X., and Yang H., 2009: Using MODAWEC to generate daily weather data for the EPIC model. Environmental Modelling & Software 24 (5): 655-664.

Luc Descroix, Ibrahim Bouzou Moussa, Pierre Genthon, Daniel Sighomnou, Gil Mahé, Ibrahim Mamadou, Jean-Pierre Vandervaere, Emmanuèle Gautier, Oumarou Faran Maiga, Jean-Louis Rajot, Moussa Malam Abdou, Nadine Dessay, Aghali Ingatan, Ibrahim Noma, Kadidiatou Souley Yéro, Harouna Karambiri, Rasmus Fensholt, Jean Albergel and Jean-Claude Olivry., 2013: Impact of Drought and Land – Use Changes on Surface – Water Quality and Quantity: The Sahelian Paradox, Current Perspectives in Contaminant Hydrology and Water Resources Sustainability, Paul Bradley (Ed.), ISBN: 978-953-51-1046-0, InTech, DOI: 10.5772/54536. Online at:http://www.intechopen.com/books/current-perspectives-in-contaminant-hydrology-and-water-resources-sustainability. Accessed on 01/03/2014.

Mertens J., Liechti Cohen, T., Matos, J. P., Tilmant, A., Schleiss, A.J., Wehrli, B., 2013: Adapted reservoir management in the Zambezi river basin to meet environmental needs. International Journal on Hydropower and Dams, 2, 80-84

Miao1 L., Jun, X,. and Dejuan,. M., 2012: Long-term Trend Analysis of Seasonal Precipitation for Beijing, China. J. Resour. Ecol. 2012 3 (1) 064-072.

Molina A, Vanacker V, Balthazar V, Mora D, and Govers, G., 2012: Complex land cover change, water and sediment yield in a degraded Andean environment. Journal of Hydrology 472–473 (2012) 25–35.

MTENR (2007): Formulation of the National Adaptation Programme of Action on Climate Change. Government of the Republic of Zambia. Lusaka.

Mucheleng'anga C.G, Turton A.R, Mbawo E, Ng’oma M, Mukubesa L.L, and Musonda W.C .,2002: Water Demand Management, Natural Resource Reconstruction And Social Adaptive Capacity: A Case Study From Chongwe-Chalimbana Area Of Zambia, CD-ROM produced by: Water Research Commission (WRC), Paper presented at the Biennial Conference of the Water Institute of Southern Africa (WISA), 19 – 23 May 2002, Durban, South Africa, ISBN Number: 1-86845-844-X

Mulenga C. L., 2003: Urban Slums Reports: The case of Lusaka, Zambia. Online at http://www.ucl.ac.uk/dpu-projects/Global_Report/pdfs/Lusaka.pdf . Accessed on 14/03/2014.

Nieuwolt S., 1971: Climatic variability and weather types in Lusaka, Zambia, Archiv für Meteorologie, Geophysik und Bioklimatologie, Serie B , Volume 19, Issue 4, pp 345-366.

Pena Arancibia, J.L. 2012: Impacts of land use change on dry season flows across the tropics. Forests as 'sponges' and 'pumps. Doctoral dissertation, University of London, May 2013, 262 pp.

Peña-Arancibia J.L.; van Dijk, Albert I.J.M.; Guerschman, J. P.; Mulligan M; (Sampurno) Bruijnzeel, L. A; McVicar, TR., 2012: Detecting changes in streamflow after partial woodland clearing in two large catchments in the seasonal tropics. Journal of Hydrology vol. 416-417. p. 60-71

Pettitt A.N., 1979: A non-parametric approach to the change-point problem. J. Royal Statist. Soc. Ser. C (Appl. Statist.) 28, 126–135.

Rose S and Peters, N.E., 2001: Effects of urbanization on streamflow in the Atlanta area (Georgia, USA): a comparative hydrological approach. Hydrol. Process. 15, 1441–1457.

Sahin V., Hall, M.J.,1996: The effects of afforestation and deforestation on water yields. Journal of Hydrology 178 (1/4), 293–309.

Sakeyo E.K., 2008: Modelling the Impact of Deforestation on Stream Flow – A Case of Chalimbana River Catchment In Chongwe, Zambia (unpublished). Research Thesis in partial fulfilment of the requirements for the degree of Master of Science in Water Resources and Livelihood Security, Department of Water and Environmental Studies, Linköpings Universitet, Sweden. "Stored: http://www.diva-portal.org/smash/record.jsf?pid=diva2:17514"

Schelle P and Pittock, J., 2005: Restoring the Kafue Flats : A partnership approach to environmental flows in Zambia, Global Freshwater Programme, WWF International.

Scott D.F., Prinsloo, F.W., Moses, G., Mehlomakulu, M., Simmers, A.D.A., 2000: A re-analysis of the South African afforestation experimental data. Water Research Commission, WRC Report No. 810/1/00, South Africa 2000.

Sharda V.N., Samraj, P., Samra, J.S., Lakshmanan, V., 1998: Hydrological behaviour of first generation coppiced bluegum plantations in the Nilgirl sub-watersheds. Journal of hydrology 211 (1–4), 50–60.

Smakhtin V. Y., 1999: Generation of natural daily flow time-series in regulatedrivers using a non-linear spatial interpolation technique, Regul. Rivers: Res. Mgmt., 15, 311–323.

Smakhtin V. Y., 2001: Low flow hydrology: a review, J. Hydrol., 240,147–186.

Spinello A.G., Simmons D.L., 1992: Base Flow of 10 South-Shore Streams, Long Island, New York, 1976–85, and the Effects of Urbanization on Base Flow and Flow Duration. Reston, Va: US Geological Survey. Water-Resources Investigations Report 90-4205.

Surur A.N., 2010: Simulated impact of land use dynamics on hydrology during a 20-year-period of Beles basin in Ethiopia (unpublished). Master of Science Thesis in Water System, Technology Department of Land and Water Resources Engineering, Royal Institute of Technology (KTH), SE-100 44 STOCKHOLM, Sweden. "Stored: http://www2.lwr.kth.se/Publikationer/PDF_Files/LWR_EX_10_04.pdf"

Tharme R.E., 2003: A global perspective on environmental flow assessment: Emerging trends in the development and application of environmental flow methodologies for rivers:River Research and Applications, v. 19, p. 397–442.

The Republic of Zambia - Forest Department., 1976: Vegetation map 1:500,000. Atlas of 9 maps sheets; sheet number 7; Zambia.

Uhlendahl T., Salianb P,. Casarottoc C and Doetschd J., 2011: Good water governance and IWRM in Zambia: challenges and chances, Water Policy 13 (2011) 845–862, IWA publishing, 2011.

USGS 2008: Water Basics Glossarry. Online on: http://water.usgs.gov/water-basics_glossary.html . Accessed on 15/04/14.

Vandegrift T. R., and Stefan H.G., 2010: Annual Stream Runoff and Climate in Minnesota's River Basins. University of Minnesota, St. Anthony falls laboratory Engineering, Environmental and Geophysical Fluid Dynamics. Project Report No. 543.

Wagesho N., 2014: Catchment dynamics and its impact on runoff generation: Coupling watershed modelling and statistical analysis to detect catchment responses. International Journal of Water Resources and Environmental Engineering, Vol. 6(2), pp. 73-87.

Water Resources Management Act, 2011. GOVERNMENT OF ZAMBIA. ACT No. 21 of 2011. Date of Assent: 15th April, 2011 online on www.parliament.org.zm, cit. 11/06/ 2013.

Yan B, Fang N.F, Zhang P.C and Shi, Z.H., 2013: Impacts of land use change on watershed streamflow and sediment yield: An assessment using hydrologic modelling and partial least squares regression. Journal of Hydrology 484 (2013) 26–37

Yao Y., Cai. T., Wei. X., Zhang., M. and Ju C., 2011: Effect of forest recovery on summer streamflow in small forested watersheds, Northeastern China. Hydrological Processes, vol. 26, issue 8, pp. 1208-1214.

Yue S., and Wang C.Y., 2002: Applicability of prewhitening to eliminate the influence of serial correlation on the Mann–Kendall test. Water Resour. Res. 38 (6), 1068.

Zhang Q, Liu C L, Xu C Y and Jiang T., 2006: Observed trends of annual maximum water level and streamflow during past 130 years in the Yangtze River basin, China. Journal of Hydrology, 324: 255–265.

Zhang X., Yu X., Wu S., Zhang M., Li J., 2007: Response of land use/coverage change to hydrological dynamics at watershed scale in the Loess Plateau of China. Acta Ecologica Sinica, 2007, 27(2), 414−423.

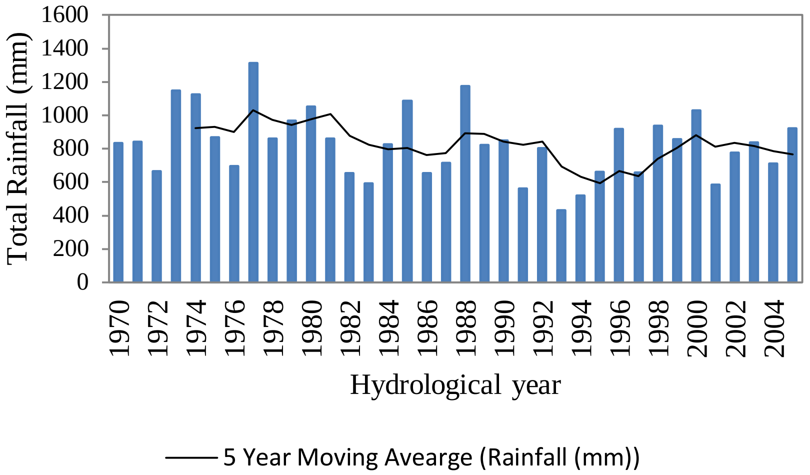
Zhang L., Zhao, F.F., and Brown A. E., 2012: Predicting effects of plantation expansion on streamflow regime for catchments in Australia. Hydrol. Earth Syst. Sci., 16, 2109–2121.

Zhang L., Dawes, W.R., and Walker G.R., 2001: Response of mean annual evapotranspiration to vegetation changes at catchment scale. Water Resources Research 37 (3), 701–708.

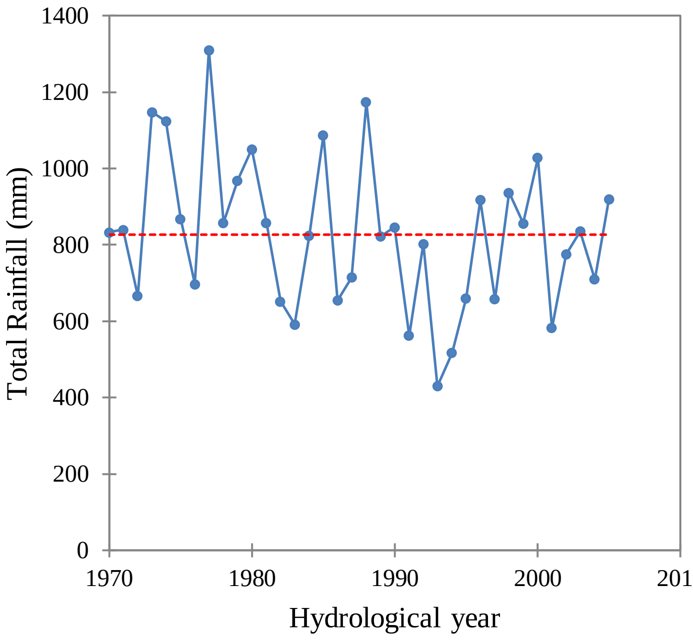
Zhang W., Yan Y., Zheng J., Li, L., Dong X., and Cai H., 2009: Temporal and spatial variability of annual extreme water level in the Pearl River Delta region, China. Global and Planetary Change 69 (2009) 35–47.

APPENDICES

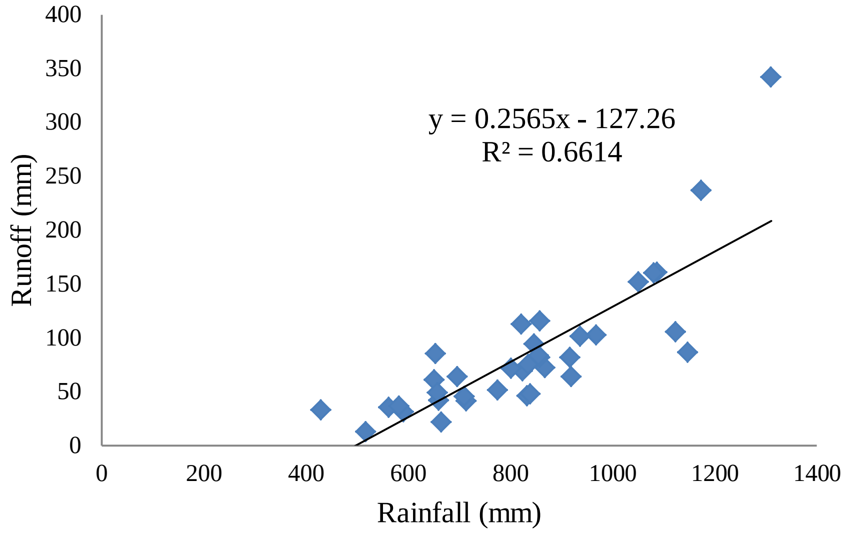
Appendix 1: Long Term variation in Rainfall totals in Chongwe catchment



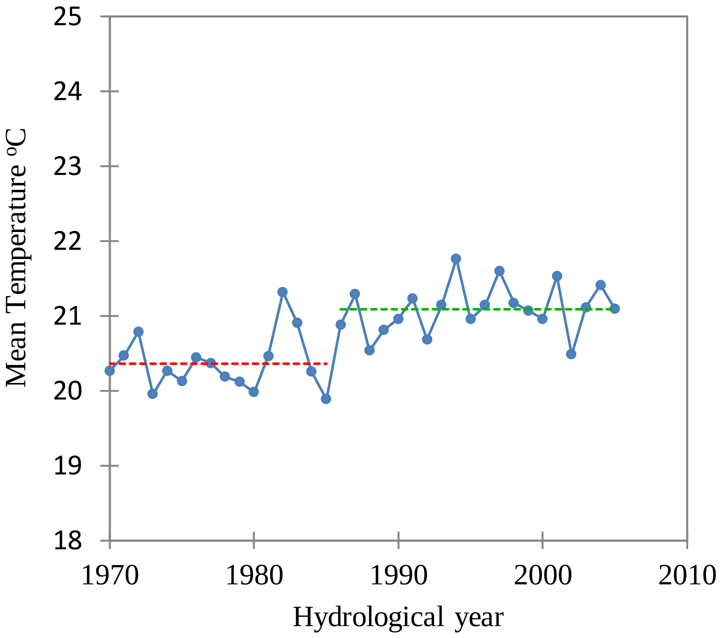
Appendix 2: Average Rainfall (mm) at KK and Lusaka city airport from 1970-2005



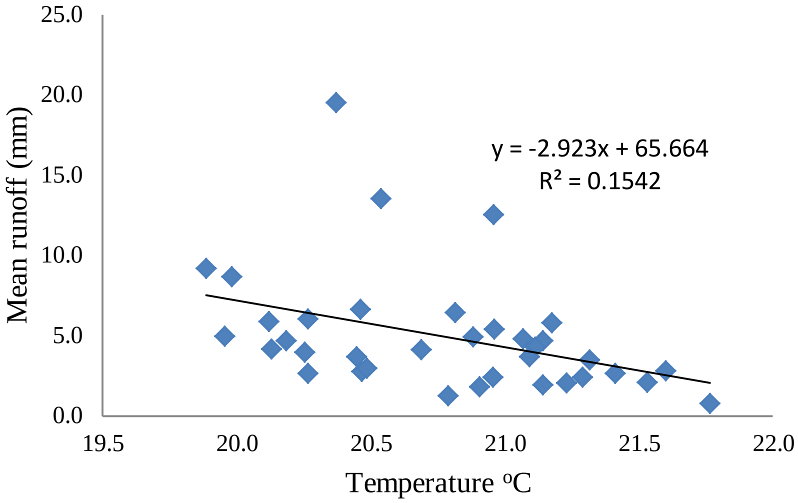
Appendix 3: Total annual Rainfall vs Mean Annual runoff at Chongwe 5025



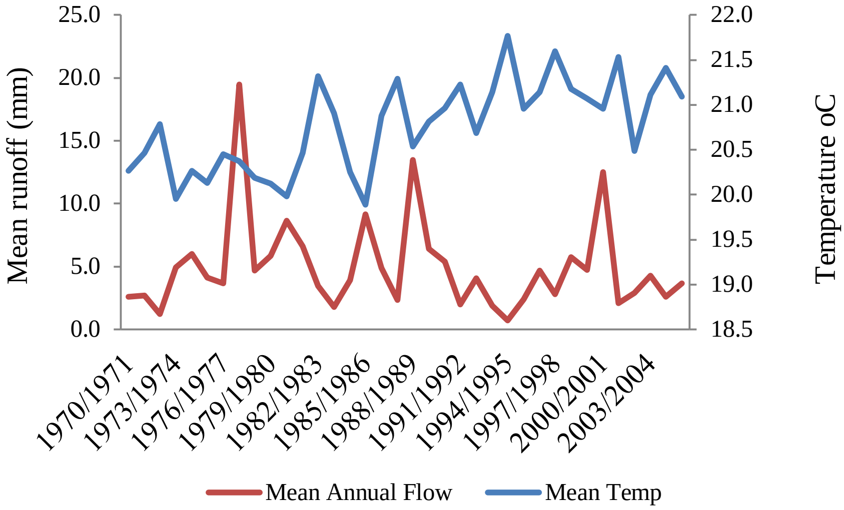
Appendix 4: Time of Change in Temperature at stations in Chongwe



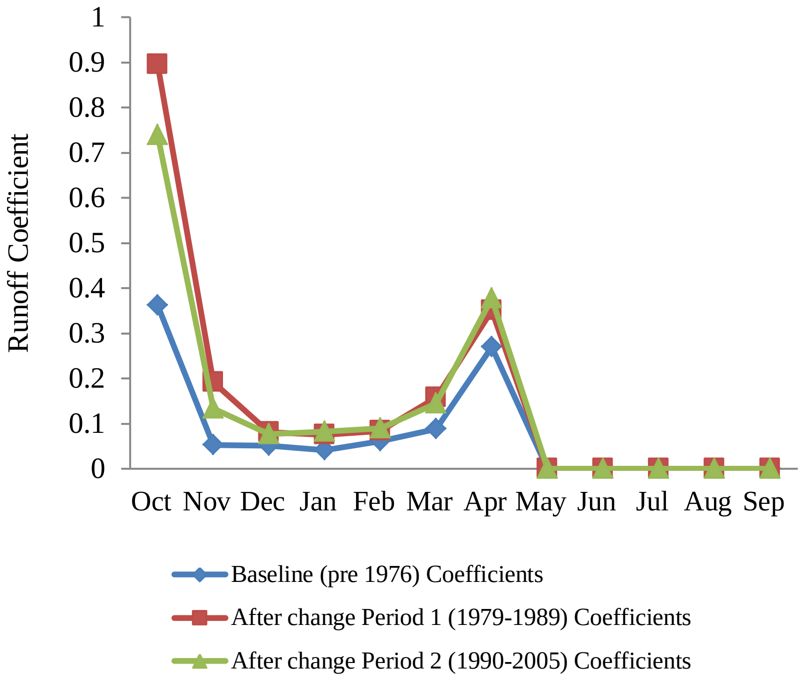
Appendix 5a: Relationship between total Temperature and Runoff at Chongwe 5025



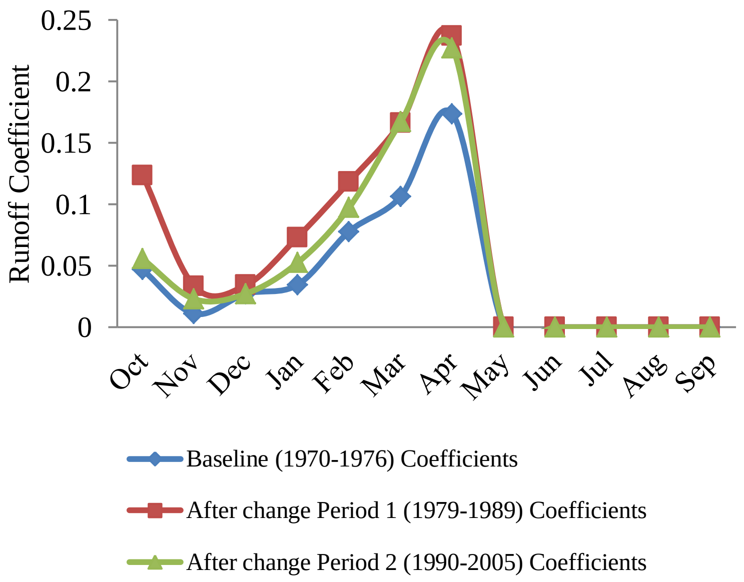
Appendix 5b: Relationship between total Temperature and Runoff at Chongwe 5025



Appendix 6: Average Monthly Runoff Coefficients at Ngwerere (5016)



Appendix 7: Average Monthly Runoff Coefficients at Chongwe (5025)



Appendix 8: Flow Indices and their associated discharges at Ngwerere weir *(Extracted figure 5.10 giving Annual FDCs at Ngwerere weir)*

Flow indices	1971/1972 (Discharge (m^3/s)	1975/1976 (Discharge (m^3/s)	1984/1985 (Discharge (m^3/s)	1990/1991 (Discharge (m^3/s)	2003/2004 (Discharge (m^3/s)	2005/2006 (Discharge (m^3/s)
Q95	0.31	0.326	0.332	0.534	0.374	0.34
Q90	0.313	0.333	0.356	0.576	0.389	0.38
Q75	0.344	0.38	0.448	0.61	0.412	0.424
Q50	0.366	0.412	0.507	0.65	0.458	0.5
Q25	0.4	0.448	0.534	0.721	0.518	0.813
Q10	0.457	0.495	0.7	0.865	0.673	1.381
Q5	0.517	0.537	0.79	0.918	0.744	1.793

Appendix 9: Flow Indices and their associated discharges at Chongwe 5025 *(extracted figure 5.11giving Annual FDCs at Chongwe 5025)*

Flow indices	1971/1972	1975/1976	1984/1985	1990/1991	2003/2004	2005/2006
Q95	0.551	0.69	0	1.485	0	0
Q90	0.702	0.875	0.002	1.615	0	0
Q75	1.422	1.782	0.982	2.037	0.21	0.203
Q50	1.782	2.577	1.875	2.438	2.954	2.031
Q25	2.339	3.998	3.998	6.429	5.157	5.887
Q10	4.82	8.785	7.405	11.965	8.89	9.031
Q5	7.237	13.196	13.944	21.154	15.366	11.34