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Assessment of environmental flow requirements in Buzi River basin, Mozambique

Lovisa Lagerblad

ABSTRACT

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Rivers belong to the world's most complex ecosystems but increasing demands for water are degrading rivers worldwide. The increase in human populations and activities has resulted in an intense and difficult conflict between the development of rivers as a natural resource and their function as living ecosystems. It is now widely recognized that a naturally variable flow regime is required to sustain freshwater ecosystems. Many countries that experience river degradation have started to implement environmental flows, i.e. the unallocated flow purposely preserved in a river.

The objectives of this thesis are twofold. The first aim is to briefly describe the concept and science of environmental flows and the different methodologies for calculating environmental flows. This was done based on a literature review of the subject. The second aim is to present a case study calculating the environmental flow requirements. The case study was conducted through a field study in the Buzi River basin in Mozambique and the subsequent modeling of the environmental flow requirements.

The literature study showed that not only the quantity of water is important; the timing and frequency of floods, droughts, low flows and high flows are very important as well. The literature study also showed that the advances in environmental flow science have been remarkable while the water policy and management has not been equally successful in implementing environmental flow standards.

The calculation of environmental flow requirements was done with the *Desktop Reserve Model* developed in South Africa. The results indicated that to maintain the ecological status in the Buzi River at a largely natural condition (ecological category A) an average allocation of 57 % of mean annual runoff (MAR) is required. The present ecological status was determined in Revue River, which is one of the three major tributaries to Buzi River. To maintain the Revue River at its present ecological state requires an environmental flow between 23-37 % of MAR.

The major environmental threats in Revue River are erosion and flow modification. The erosion is a consequence from artisanal gold mining, inadequate farming practices and deforestation. The flow alterations are caused by the large Chicamba Dam constructed for the generation of hydropower.

One of the questions this thesis aimed to answer was if it was possible to set the present ecological state with a limited amount of data. This study showed that it could be possible but that the confidence level will be low. The relationships between ecological metrics and flow alterations must be investigated in detail for this region before environmental flow requirements can be successfully calculated and implemented.

Keywords: environmental flows, environmental flow requirements, present ecological state, Buzi River basin, Desktop Reserve Model, Mozambique

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REFERAT

Utvärdering av miljöanpassade flöden i Buzi avrinningsområde, Moçambique
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Floder hör till jordens mest komplexa och känsliga ekosystem, men ett ökat tryck på våra vattenresurser har försämrat situationen för många av världens floder. Befolkningsökningen och den globala utvecklingen har resulterat i en intensiv och komplicerad konflikt mellan utnyttjandet av floder som en naturresurs och bevarandet av deras funktion som unika ekosystem. Det är nu allmänt accepterat att den naturliga flödesvariabiliteten behövs för att bevara våra sötvattenekosystem. Flera länder där försämringen av floder är ett faktum har börjat införa *miljöanpassade flöden*, det vill säga vatten som medvetet tilldelas flodens ekosystem.

Det finns två syften med det här examensarbetet. Det första är att genom en litteraturstudie beskriva miljöanpassade flöden och de modeller som används för att beräkna detta flöde. Det andra målet är att göra en fallstudie och beräkna det miljöanpassade flödet och bestämma den ekologiska statusen för Buzi floden i Moçambique.

Litteraturstudien visade att det inte bara är kvantiteten av vatten som är viktigt; tidpunkt och återkomsten av översvämning, torka, lågflöden och högflöden är mycket viktiga om man vill efterlikna det naturliga flödet. Litteraturstudien visade även att framstegen i kunskapen om miljöanpassade flöden har varit stora medan vattenlagstiftningens anpassning och införandet av miljöanpassade flöden har varit svag i flera avseenden.

Modellerandet gjordes med den sydafrikanska *Desktop Reserve Model*. Resultaten från modellen visade att för att bibehålla den ekologiska statusen för Buzi floden i ett nära naturligt stadium (ekologisk klass A) krävs en tilldelning på 57% av medelårsavrinningen. Den nuvarande ekologiska statusen bestämdes i Revue floden, som är en av tre huvudfloder i Buzi avrinningsområdet. För att behålla Revue floden i sitt nuvarande tillstånd skulle kräva ett miljöanpassat flöde på mellan 23-37% av medelårsavrinningen.

De största ekologiska hoten i Revue floden visade studien var erosion och flödesförändringar. Erosionen är en konsekvens av guldutgrävning, jordbruk med fel teknik, och skogs-avverkning. Flödesförändringarna härrör från den stora vattenkraftsstationen Chicamba Dam.

En av frågorna den här studien syftade till att besvara var om det är möjligt att bestämma den nuvarande ekologiska statusen med en begränsad tillgång till data. Studien visade att det är möjligt men att osäkerhetsnivån i resultatet kommer att vara stort. Studien visade även att modellen *Desktop Reserve Model* kan användas för snabba beräkningar av det miljöanpassade flödet, men att mer utförliga studier som till exempel *Building Block Methodology* måste genomföras innan resultatet med säkerhet kan verifieras. Relationen mellan ekologiska förändringar och flödesvariationer måste utredas i detalj för studieområdet innan de miljö-anpassade flödesbehoven kan bli implementerade med framgång.

Nyckelord: miljöanpassade flöden, miljöanpassade flödesbehov, nuvarande ekologisk status, Buzi avrinningsområde, Desktop Reserve Model, Moçambique

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PREFACE

This work is a master thesis of 30 ECTS within the Master of Science program in Aquatic and Environmental Engineering at Uppsala University, Sweden. The project has been carried out for Sweco Environment, in Stockholm and Pretoria. Supervisor in Stockholm was Daniel Persson and supervisor in Pretoria was Rikard Lidén. Subject reviewer was Birgitta Malm-Renöfält at the Department of Ecology and Environmental Sciences, Umeå University, Sweden. The project was financed by Uppsala University and the Swedish Association of Graduate Engineers.

A parallel master thesis has been carried out by Stéphanie Nicolin. The two of us spent the two months in South Africa and Mozambique together, and without her this project would not have been as exciting and enjoyable as it has been. So I would like to thank you Stéphanie for all laughters, support and company during this project.

Great thanks to Rikard Lidén who narrowed down the objectives and made the field visit to Mozambique and the time in South Africa possible. Without your ideas and engagement we would never have been able to go to Africa.

Emelie Arnoldsson who arranged with accommodation, showed us Kruger and the big five and taught me to drive on the left side, you helped us out a lot, thanks.

To all staff at BKS Water Resources in Pretoria I would like to say a big thank you for being so welcoming and friendly. Estelle van Niekerk who helped with the modeling, you did great job teaching me the Desktop Reserve Model and much more in such a short time. Thanks also to Jonathan Schroder for being patient with the giggling Swedes and teaching us a lot.

To the staff at ARA-Centro I would like to show my gratitude for answering all our questions. Specially to Antonio Melembe who happily drove us around and guided us in Buzi River basin, your local knowledge and contacts made it possible for us to visit all the sites we were interested in, without you the fieldwork could not have been carried out.

Thanks to Birgitta Malm-Renöfält for the input on my master thesis, Anna Forslund, Denis Hughes, and to all others who have been a part of this project either through answering questions, supporting, helping out with practicalities, being friendly or just encouraging.

Finally I would like to thank Markus Brolin for encouraging me to go to Africa and supporting me through the whole project.

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POPULÄRVETENSKAPLIG SAMMANFATTNING

Utvärdering av miljöanpassade flöden i Buzi avrinningsområde, Moçambique

Lovisa Lagerblad

För varje år kommer dagen då vi människor lever över våra tillgångar allt närmare, i år inföll den redan i augusti, förra året var det i september. Vi människor hushåller inte med våra naturresurser och konsekvenserna av detta kan bli och är redan ofattbara. Globalt sett är miljonstals människor beroende av de tjänster som floder, vattendrag, åar och bäckar ger. Vi nyttjar inte vattnet enbart för konsumtion, utan vi har lärt oss utnyttja kraften i strömmande vatten till vattenkraft, använda kanaler för att bevattna jordbruk, floder för transport, listan kan göras lång. Men liksom med flera av jordens andra resurser klarar inte våra floder av den extremt hårda press vi utsätter dem för.

Den intensiva och komplicerade konflikten mellan utnyttjandet av floder som en naturresurs och bevarandet av deras funktion som unika ekosystem är vad det här examensarbetet har tittat närmare på. Ett koncept som kallas *miljöanpassade flöden* (engelska *environmental flows*) handlar om hur man avsiktligt ska bevara en viss del av vattnet i en flod för flodens ekosystem. Det är inte bara en fråga om mängden vatten, utan det är också en fråga om tid och varaktighet av det vatten man låter floden behålla.

Konceptet miljöanpassade flöden bygger på att man antar att flodens ekologiska status kan bibehålla en viss bestämd nivå vid en avsatt mängd vatten. Beroende på vad flodens nuvarande och framtida användningsområde är kan den förbestämda nivån variera. Till exempel en flod som i dagsläget är mycket hårt belastad av vattenkraftverk kommer att ha en lägre status än en orörd flod i ett naturreservat. Klassificering av ekologisk status kan göras på flera nivåer, men gemensamt är att man studerar relationen mellan ekologiska förändringar och flödesvariationer.

Studien genomfördes först genom en litteraturstudie inom ämnet miljöanpassade flöden. Med hjälp av litteraturstudien kunde information om lämpliga modeller inhämtas. Litteraturstudien gav även bakgrundsfakta till varför det är så viktigt med perioder av översvämningar, torka, lågflöden och högflöden. Efter litteraturstudien genomfördes en fältstudie till Buzi avrinningsområde i centrala Moçambique. Fältstudien hade som huvudsyfte att fastställa den nuvarande ekologiska statusen på delar av floden.

Buzi är idag en relativt outnyttjad flod. Ett stort vattenkraftverk med en tillhörande damm på 120 km^2 ligger i en av de tre stora bifloderna och vatten från floden används även till mindre bevattningar av sockerrör och andra grödor. De miljöproblem som den här studien visade på i Buzi var ökade halter av finkornigt material; sediment, som gör vattnet rödgrumligt. Den höga sedimenthalten kan bland annat leda till att fiskar får problem med gälarna, solljus inte når ner till växterna och reservoarer och kanaler fylls igen med mera. Ett annat problem som observerades var att strandbankerna var hårt utsatta för erosion. Regleringen av utflödet från dammen utgör en förändring av den naturliga flödesvariabiliteten vilket kan orsaka rubbningar i det naturliga ekosystemet.

Efter fältstudien och undersökningar av flodens nuvarande ekologiska status modellerades det miljöanpassade flödet. Modellerandet gjordes med en Desktop Reserve Model ursprungligen konstruerad för Sydafrika och de förhållanden som råder där. Det antogs dock att modellen skulle fungera även för Moçambique. Resultaten från modellen visade att för att bibehålla den ekologiska statusen i ett nära naturligt stadie (ekologisk klass A) kräver en tilldelning på 57% av medelårsavrinningen. Den nuvarande ekologiska statusen bestämdes i Revue floden, som är en av tre huvudfloder i Buzi flodområde. För att behålla Revue floden i sitt nuvarande tillstånd skulle kräva ett miljöanpassat flöde på mellan 23-37% av medelårsavrinningen.

De här siffrorna visar hur stor mängd vatten som under ett år behöver finnas kvar i floden för att den ska uppnå eller bibehålla en viss status. Som tidigare nämnts är även tidpunkten och varaktigeten av när vattnet ska finnas i floden viktigt. Det naturliga flödet består av en period med höga flöden från december till april och en period med låga flöden från juni till november. Det miljöanpassade flödet för perioden med höga flöden visar att en stor del av vattnet är tillgängligt för till exempel bevattning, men under perioder med låga flöden är det väldigt små mängder vatten som kan tas från floden. Detta kan vara problematiskt då till exempel behovet av bevattning oftast är som störst då det regnar som minst, alltså då de naturliga flödena i floden är små. I sådana här fall kan det vara bra att bygga en damm för att underlätta för floden och de som behöver vatten för bevattning under de perioder då flödena är mycket små.

Införandet av miljöanpassade flöden är svårt. Dels är det svårt att förutsäga hur kommande dagarnas eller månadernas flöden kommer bli. Dels är det svårt att reglera och kontrollera att ingen vattenanvändare tar ut mer än sin tilldelade andel. Det är faktiskt så svårt att införa miljöanpassade flöden att det inte gjorts fullt ut någonstans i hela Sydafrika, trots att man i stort sett har beräknat de miljöanpassade flödena på alla större floder man har.

Det här examensarbetet visar att det med små medel och begränsad mängd data går att göra en grov uppskattning på den nuvarande ekologiska statusen och rekommenderade miljö-anpassade flöden. Resultaten kan användas till att liknande studier genomförs, där en första grov uppskattning görs för hur man bör använda vattnet i floden för att ändå bibehålla dess naturliga ekosystem. Det visar att vi människor kan använda oss av ganska stora mängder vatten utan att floden tar någon nämnvärd skada, men vi måste lära oss förstå och tolka samspelet mellan flöden och ekologisk påverkan. Inom det området finns det mycket kvar att göra.

ACRONYMS AND DEFINITIONS

BBM – Building Block Methodology

BFI – Base Flow Index

CV – Coefficient of Variation

CVB – Hydrological Index

DRM – Desktop Reserve Model

EFR – Environmental Flow Requirement

EFA – Environmental Flow Assessment

SPATSIM – Spatial and Time Series Information Modelling Software

EIS – Ecological Importance and Sensitivity

DWA – Department of Water Affairs (old name is DWAF)

FDC – Flow Duration Curve

MAR –Mean Annual Runoff

PES – Present Ecological State

REC – Recommended Ecological Category

Environmental flows - "Environmental flows describe the quantity, quality and timing of water flows required to sustain freshwater end estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems." (Brisbane Declaration, 2007)

Sustainable development –" Development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission on Environment and Development WCED, 1987)

Integrated Water Resource Management IWRM - IWRM approaches ensure that water resources are managed as ecosystems. It also implies that coordination between regions is essential to ensure sustainable use of this resource (UNEP, 2006).

Ecological status -"The totality of the features and characteristics of the river and its riparian areas that bear upon its ability to support an appropriate natural flora and fauna and its capacity to provide a variety of goods and services." (Kleynhans & Louw, 2007).

River basin – the entire geographical area drained by a river and its tributaries

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1 INTRODUCTION

Water resources and river basins

The availability of water is one of the most basic conditions for sustainable development. The accessibility of freshwater per person is constantly decreasing, mainly due to population growth (Stikker, 1998). Nowhere is the problem more urgent than in developing countries, particularly in arid climates where the population already relies on very limited water resources. Human links to river ecosystem services are also strongest in these countries. Still uncounted, the number of people globally depending on river systems must be in the order of hundreds of millions (e.g. Corbett, 2000). 0.3% (118639 trillion liters) of the world's freshwater is found in lakes, rivers and wetlands, but increasing demands for water are degrading rivers worldwide (King *et al.*, 2003). The problem is already visible in many river basins where the rivers no longer reach the sea due to over extraction upstream. Some examples are the Yellow River (China), Ganges (Nepal, India and Bangladesh), Indus (Pakistan, India, China and Afghanistan) and the Nile, bordered by ten nations in Africa, to name but few. The only remaining large free-flowing rivers in the world are found in the tundra regions of North America and Russia, and in smaller coastal basins in Africa and Latin America (Nilsson *et al.*, 2005).

Conflict

Rivers ignore political boundaries, and transboundary waters require international sharing. Each basin state is entitled to a reasonable and equitable share of the water, which was stated in the Helsinki rules on the Uses of the Waters of International Rivers drawn in 1966 (UNECE International Law Association, 1967). Water-related disputes revolve around one or more of three issues: quantity, quality and timing. The conflicts can occur between different sectors, upstream and downstream users or between countries. One example of a quantity and quality dispute is the Incomati River flowing through South Africa and Mozambique. Dams and water transfers in the South African part caused reduced freshwater flows and increased salt levels in Mozambique's Incomati estuary. This impact changed the ecosystem balance and important plants and animals disappeared, which affected people's livelihoods (UNEP, 2005a).

River degradation

Rivers belong to the world's most complex ecosystem. The expansion of human populations and activities has resulted in an intensifying and difficult conflict between the development of rivers and their function as living ecosystems (Dynesius & Nilsson, 1994). Flow alterations can have severe consequences for both ecosystems and humans; stress and loss of organisms, dominance of competitive species, reduced habitat availability (Renöfält *et al.*, 2009) arid river deltas, less nutrients to serve irrigated agricultural land and fisheries (Stikker, 1998). The enormous increase in the number of dams has severely changed the flow of roughly 60% of the world's major river basins (Revenga *et al.*, 2000). In Africa at least 114 new major dam developments, mostly for hydropower generation, are either under construction or survey (Cartney & Matthew, 2007).

Environmental Flows

Many of the countries that experience river degradation know that environmental protection must be part of their aquatic resources management (King *et al.*, 2003). Internationally the importance of maintaining sustainable river basins, by reserving some water along the river, is growing (Mazvimavi *et al.*, 2007; King *et al.*, 2003; Hughes & Hannart, 2003). Environmental Flow Assessments (EFAs) produce one or more descriptions of possible modified flow regimes for the river, thus the Environmental Flow Requirements (EFRs), connected to a predetermined recommended ecological status. The origin of the environmental flow concept was in the 1940s and today at least 207 individual methodologies, within six main types, were recorded in use for 44 countries, within six broad world regions (Tharme, 2003). The methods have developed from simple rule-of thumb guidelines often aimed at one or a few particular organisms, to holistic methods encompassing the entire ecosystem and the intra-, and inter year variability in flow. The awareness of river degradation has been conducive to that environmental flows are increasingly appearing on national and international political agendas and the requirement to use them in legislation (King *et al.*, 2008). Environmental flows can be said to be the unallocated flow purposely preserved in a river. During the Brisbane Declaration (2007) the most widely held definition, which will be used in this thesis, was developed:

"Environmental flows describe the quantity, quality and timing of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems."

An example of when environmental flows have been used is the in Great Ruaha River catchment in Tanzania. The area has experienced zero flows during the dry season, resulting in conflicts between upstream and downstream users. The study was performed with a method called Desktop Reserve Model (DRM), which also will be used in the case study from Buzi River basin presented further into this thesis. The result shows that to maintain the basic ecological functioning of the Great Ruaha River require an average water allocation of 635 Mm^3/a, equivalent to 21.6% of mean annual runoff (MAR) (Kashaigili *et al.*, 2007).

1.1 PROJECT BACKGROUND

An area where the sustainable uses of rivers are very important is in south-eastern Africa. The water resources in the river basins are valuable and necessary for the regions development. With the purpose to secure the water availability, an Integrated Water Resources Management (IWRM) strategy will be established. Southern African Development Community (SADC, Box 1) started year 2005 "A regional strategic action plan on integrated water resources development and management" and a part of this project is the "Shared watercourses support project for the Buzi, Ruvuma and Save river basins" in Mozambique, Tanzania and Zimbabwe. The project implementation started in 2008 and is funded by the African Development Fund. The objective of the project is to ensure a sustainable framework for the shared water resources and to improve the livelihoods of the people and to protect the environment.

SWECO, a Swedish technical consultancy firm, works as the lead consultant for the Buzi and Ruvuma shared watercourses support projects. This master thesis is done in cooperation with SWECO, who helped with tutoring, information and support. One of the responsibilities for SWECO is to determine the environmental flow requirements for the rivers. As this science is quite new there was an interest for some extra input and research on environmental flows and that is the cornerstone of this thesis.

Box 1: Short description of Southern African Development Community (SADC) (SADC, 2009).

> The origins of SADC started in 1980 with the aim to reduce the economic dependence on the then apartheid South Africa. Today it works for improvements of the standards of living and quality of life, freedom and social justice; peace and security for the people of Southern Africa. The Regional Water Policy (2005) is a keystone towards the goal of regional integration and poverty eradication. Current member stated are Angola, Botswana, the Democratic Republic of Congo, Lesotho, Madagascar, Malawi, Mauritius, Mozambique, Namibia, Seychelles, South Africa, Swaziland, Tanzania, Zambia and Zimbabwe.

1.2 OBJECTIVES

The overall objectives of this thesis are twofold. The first aim is to briefly describe the concept and science of environmental flows and the different methodologies developed for calculating environmental flows. The first aim was met through a literature review of the subject. The second aim is to present a case study calculating environmental flow requirements to gain deeper knowledge and understanding of the environmental flow assessments procedure. The case study was conducted in the Buzi River basin (Figure 1.1) in Mozambique.

The case study focused specifically on testing the applicability of one of the standard methodologies for environmental flow assessment in southern Africa. The method is based on the Desktop Reserve Model developed in South Africa (Hughes & Hannart, 2003), which is a user friendly tool and is therefore the model most used in the southern Africa region. The Desktop Reserve Model requires as one of the major inputs the present ecological status (PES) of the site evaluated. The present ecological status is a measure of how much the river's ecosystem has changed compared to its pristine condition. To decide the present ecological status requires a lot of information and data about the river, which in many situations can be difficult to obtain. The specific aim of the case study was therefore to set the present ecological status in the Buzi River basin with the presently very limited data available and to test the model's sensitivity to choice of the present ecological status.

To summarize, the case study focused on the following questions:

- Is it possible to set the present ecological status with very limited data available?
- How sensitive is the output of the Desktop Reserve Model to that the correct ecological status has been set?
- Is the Desktop Reserve Model a good and practical method for allocating water to the environment in the developing countries of southern Africa? How has the outcome of environmental flow assessments affected river management?

One hypothesis is that the result from the Desktop Reserve Model is very sensitive to the present ecological status and that a spectrum of statuses, and in consequence an interval of environmental flows, should be used to illustrate the level of uncertainty in determining environmental flow requirements.

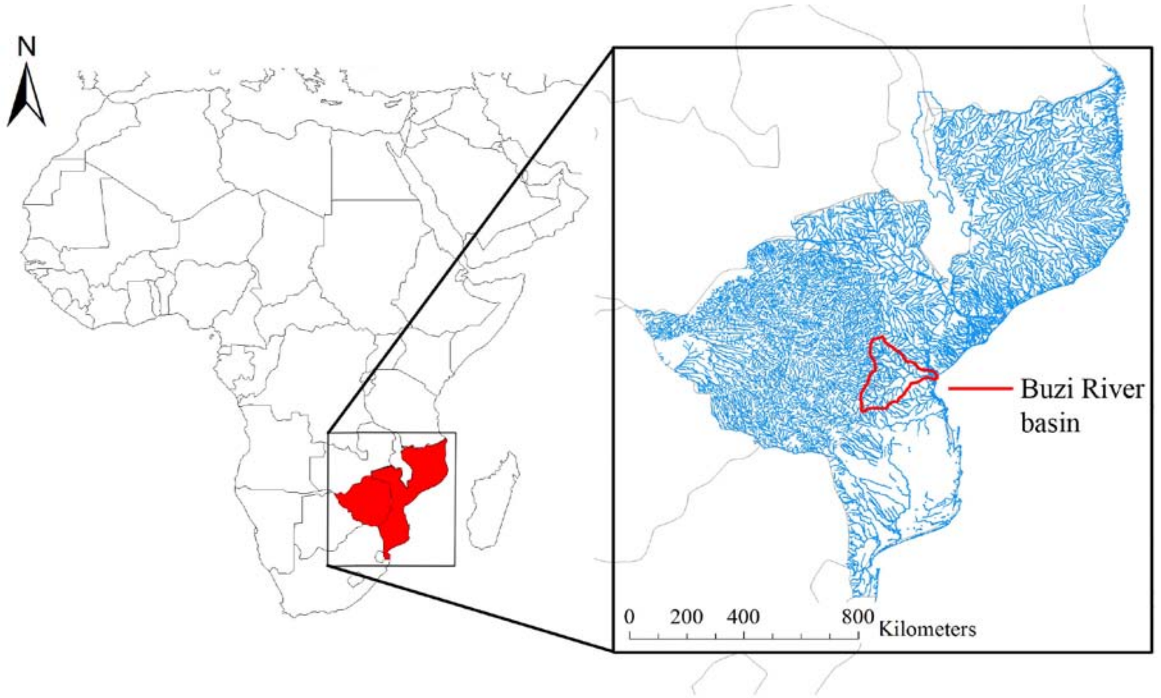


Figure 1.1: Zimbabwe and Mozambique in South-Eastern Africa. The Buzi River basin stretches over the two countries (author's map).

1.3 LIMITATIONS

The study involves the transboundary Buzi River basin shared between the two countries Mozambique and Zimbabwe. Parts of the Buzi River basin are remote and difficult to access, and a field study to all the sites could therefore not be conducted during the limited time and budget frame within this study.

According to the South African methodology there are four main categories for estimating environmental flow requirements. This study used a hydrological method. Hydrological methods use flow data for estimating the environmental flow requirements while the holistic methods require considerably more multidisciplinary expertise and input. This level of detail was not possible to set up for this study.

In South Africa the science of environmental flow assessments is well developed. A method developed by Hughes and Hannart (2003) called the Desktop Reserve Model is used in south-eastern Africa and it originated from the Building Block Methodology (BBM). As these two models have been frequently used in the region, and also by SWECO, the study was restricted to using the desktop model as user-friendly software to calculate the environmental flow requirements is available.

When talking about water resources it is common to talk about both quantity and quality, but these two aspects of water accessibility are often dealt with separately (Nilsson & Renöfält, 2008). The Brisbane Declaration (2007) definition of environmental flows mentions quantity, timing and quality of river flows. Quality is as important as quantity (Nilsson & Renöfält, 2008) and this report address both these issues, although the quantity aspect of environmental flows will have a larger part. The economical aspects of an environmental flow in terms of loss of revenue from power production or loss of revenue from decreased irrigation is not considered in this thesis. This aspect is covered in a parallel master thesis (Nicolin, 2011).

1.4 THESIS LAYOUT

This thesis begins with a background (Chapter 2) that presents the importance of environmental flows and some threats to freshwater ecosystems. Chapter 2 also briefly describes the importance of the natural flow regime and different types of flows, such as floods and low flows for maintaining a healthy and vivid ecosystem. This little glimpse into today's reality is a motivation for why it is important with this kind of study.

In Chapter 3 the literature review is presented. This chapter starts with a summary of the science of environmental flows that dates back to the 1940s till today. This chapter also presents various legislations used globally on environmental flows and discusses more in detail the situation in South Africa and Mozambique. The literature study further presents the four major types of environmental flow methodologies.

Chapter 4 describes the study area i.e. Buzi River basin and the characteristics of the hydrology and water users. The next chapter (Chapter 5) explains the methodology that were undertaken to meet the aims of the case study. Chapter 6 presents the results and these are further discussed in Chapter 7, which connects all the chapters. Finally the last Chapter 8 gives the conclusions of this study.

2 BACKGROUND

Failing to preserve some of the water in rivers, lakes or wetlands for the aquatic life affects the biodiversity strongly. Almost half of the 30 000 known species of fish lives in lakes and rivers, but freshwater animals are in general disappearing at a rate of four to six times faster than animals on land or at sea. One reason for this is that freshwater ecosystems are closely connected to human activity (Chadwick, 2010). To set a balance between human and ecosystem demands for freshwater require well developed tools and methods to minimize the negative consequences of competition for resources. According to Malmqvist & Rundle (2002) there are five principal categories of threat to freshwaters – overexploitation, water pollution, fragmentation, destruction or degradation of habitat and invasion by non-native species, and all are connected to modification of rivers, wetlands and groundwater resources. This thesis focuses on rivers, but rivers are closely related to wetlands, estuaries and groundwater resources, and they are equally important and interlinked to the surface water resources and need to be protected and preserved.

This chapter highlights some important assumptions about environmental flows. It also discusses the major features of a river system. The coming sections will also briefly describe some of the worst and most common river degradation problems and link this to environmental flows.

2.1 THE IMPORTANCE OF ENVIRONMENTAL FLOWS

An environmental flow is the amount of water that is kept flowing down a river in order to maintain the river in a desired environmental condition (O'Keeffe & Le Quesne, 2009). Rivers can be, and are, used for many things e.g. hydropower, industries, infrastructure, irrigation, drinking water, fishing, boating, recreation, cultural activities etc. All these activities must share the water and still humans and ecosystems cannot survive without adequate water resources. Environmental flows are all about using the water resources sustainable, to maintain the river in a predefined ecological state. The relation between the human need and the ecological need must be decided, and the recognition that there is a limit when a water resource suffers irreversible damage to its ecosystem functions.

Box 2. Environmental flow assessment with the BBM in Mara River Basin (WWF-EARPO, 2007 cited in Forslund *et al., 2009*)

> Mara River is a transboundary river between Tanzanian and Kenya that flows out to Lake Victoria. The flow regime in the Mara River has changed over the years mainly due to agricultural runoff and large-scale irrigation projects, and the degradation has affected the downstream ecosystems, affecting all life forms that depend on the river for support. The water policies in the two countries state that the need for environmental flows to be sustained in important river systems. The methodology used for assessing the environmental flow requirements was the Building Block Methodology (BBM). The process involved a team of scientists from various disciplines. The outcome; the environmental flow requirements, was recommended flows for base and flood flows, both in normal and dry years. Divided over the long term these recommendations are just over 50% of present flows. This shows that the river can still function well with less water, but it must be distributed more similar to the natural flow regime.

2.2 RIVERS

2.2.1 The flow regime

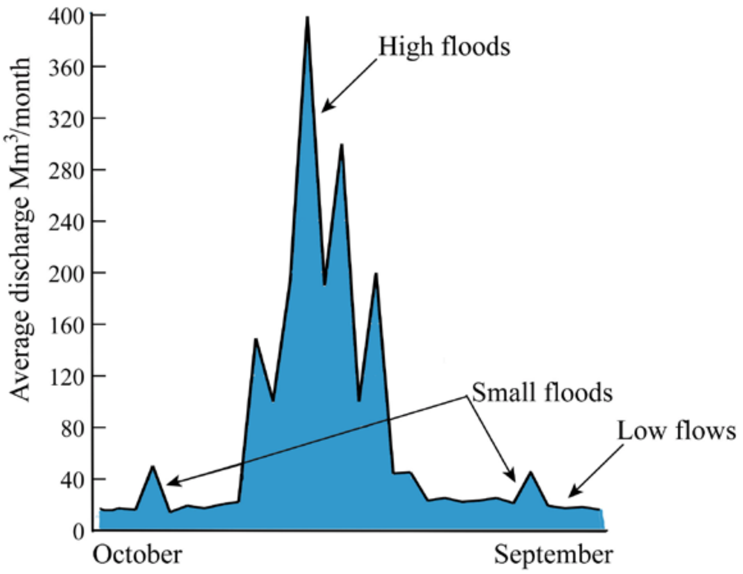


Figure 2.1. Examples of important flow features. E.g. high floods can move around life supporting nutrients and small floods trigger fish spawning.

River flow is not all about quantity of water, equally important is the timing and frequency of occurrence of these flows. The low flows define the basic hydrological nature or base flow of the river: its dry and wet seasons. A perennial river has flows all year around, as shown by the graph of the river in Figure 2.1. A seasonal river has periods of zero flows. Small floods (freshets) are important because they trigger certain reactions of the biota of the ecosystem, e.g. fish spawning or germination of riparian seedling. Freshets are also important because they dilute poor-quality water and contribute to flow variability in the river. High floods, or large floods, influence the river channel in many ways. The floods move sediments, nutrients, seeds and eggs on floodplains. They re-charge soil moisture levels on floodplains and they prevent the estuaries from being cut off from the sea by scouring (King *et al.*, 2003).

2.2.2 Ecosystem services

It is truly difficult to value the services that ecosystems provide. Benefits that humans obtains from ecosystems are of critical importance and can be local (recreation), or regional (flood regulation or nutrient cycling) and still others are global (climate adaptation). Loss of ecosystems, or even degradation, will affect human well-being (Millennium Ecosystem Assessment, 2005).

The *river ecosystem* can here simply be defined as the part of the ecosystem affected by changes in the river flow regime (Table 2.1). The benefits from river ecosystems can (in addition to scale) be divided into three major groups: water for human needs (consumption and sanitation), goods other than water, such as food and medicinal plants, and nonextractive benefits such as recreation and energy (Postel & Carpenter, 1997). Some services can also be provided directly by the water flow such as flushing of sediments. The origin of the ecosystem services can be far away from the actual point that benefits from them, for example electricity produced by hydropower in Mozambique used in Zimbabwe. In an ideal world are all ecosystem services accounted for in the environmental flow assessment. This is unfortunately not realistic, and only the most important services can be subjected to further analysis. It is the objective of the environmental flow assessment that decides which services that are most important (Korsgaard, 2006). One way to value the benefits is by economic evaluation of ecosystem services. This report will not go further into that complex issue, but Louise Korsgaard (2006) has in her Ph.D. thesis reviewed economic valuation methods for valuating ecosystem services sustained by environmental flows.

Table 2.1. The main components of a river ecosystem (adopted from Davis & Hirji, 2003)

Nonliving	**Living**
Channel, source to sea	Riparian, fringing and aquatic plants
Banks	Fish, including marine fish that use estuaries
Floodplains	Aquatic invertebrates
Linked lakes and wetlands	Aquatic mammals
Estuary	Water birds
Linked groundwater	Amphibians and aquatic reptiles
Linked near-coast marine environment	Microorganisms
Sediments	
Water chemistry and temperature	

Threats

The environmental and social impacts of large dams (higher than 15 m in height from base to crest, ICOLD, 2003) are often very complicated and difficult to forecast. Globally the modification of river flows is so extensive that the approximately 45,000 dams above 15 m high are capable of holding back 15 % of the total annual river run-off (Nilsson *et al.* 2005). In relation to reservoir volume, Africa has some of the world's largest dams, e.g. Kariba in Zimbabwe with 180 billion m^3 of storage. Furthermore, South Africa and Zimbabwe are in the top 20 countries for number of large dams, with 915 and 253 dams respectively (ICOLD World Register of Dams 2003). However, most of these dams were constructed before the 1970s and now Africa has the lowest per capita water storage of any continent (McCartney, 2007).

One of the purposes of dams is to provide hydraulic head and release water through turbines or gates on a schedule to match energy- or other water-demands (e.g. water for irrigation). Sudden peak electricity demands can result in huge daily variations. Water for irrigation is often released during growing months, when the natural flow regime is low. Since flow is the major factor of ecological processes in rivers, changes of the natural flow pattern may drastically change ecosystems (Renöfält *et al.*, 2009; Kingsford, 2000). Dams are also important for flood control as they can store water, but this requires that a part of the dam is kept empty as a backup volume for flooding.

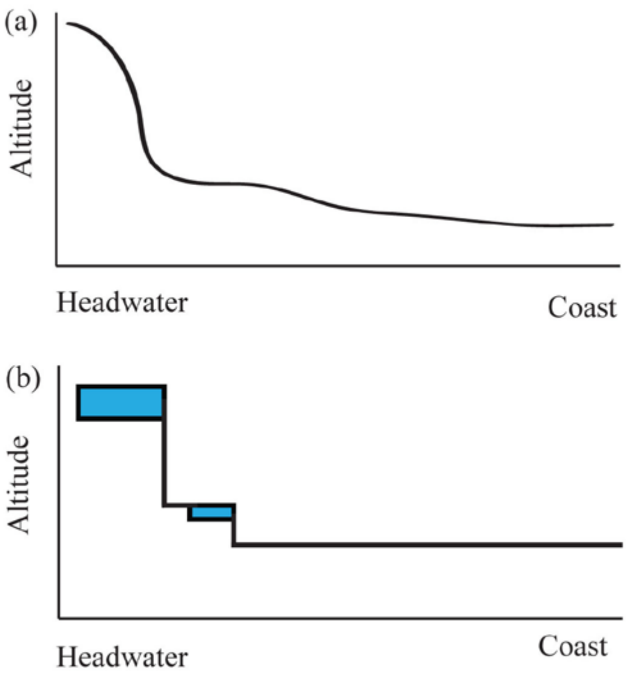


Figure 2.2. Schematic diagram showing a typical piedmont river that is steeply sloping in the upper part and has a long flat reach before it meets the coast. River (a) is unmodified while river (b) has developments in the first parts, and the lower section remains unregulated (author's figure modified from Renöfält *et al.*, 2009).

Arthington *et al.* (2009) say that an important challenge in these regulated rivers is to identify situations when small power losses can have significant positive ecological effects. Dams are therefore an important starting point to implement environmental flows. New dams also provide an opportunity to implement environmental flows from the start.

Climate change and vulnerability
Water resources availability in southern Africa is almost entirely dependent on rainfall which is seasonal. Rainfall is unevenly distributed over the area, both in time and space, and many countries have a low annual rainfall reliability. In most parts of the region potential evaporation is twice as high as rainfall totals (Hirji *et al.*, 2002). A small change in rainfall can have a large change in river flow. The combined effects of climate change on ecosystem structure and functions result in loss of resilience, and degradation in the services provided by ecosystems (Forslund *et al*, 2009). The African region seems to be overall vulnerable because of their high exposure to the effects of climate change as well as their limited possibility to adapt to them.

Hirji & Davis (2009) writes in a World Bank report that: "*Climate change is likely to make environmental flows both more important and more difficult to maintain*." Some of the reasons are affected surface and groundwater levels, changed frequency of extreme events of flood and droughts, rise in sea level, warmer temperatures and changed water requirements for irrigation.

Environmental flows are important and ecosystems are sensitive to changes in rivers. To calculate environmental flow requires a lot of knowledge about the river from the past and present state. It also requires a technical methodology and supporting legislation to be implemented. The following literature study will discuss these requirements.

3 LITERATURE STUDY

The concept of environmental flows has been around for several decades. There are approximately as many methodologies and definitions as case studies, which complicates the work to define the concept. The term environmental flow does also have many synonyms and many terms e.g. environmental water requirements and instream flow requirements are also both used to explain the same concept (Moore, 2004). The following section describes the evolution of the concept of environmental flows, and the different existing definitions.

3.1 EVOLUTION OF THE SCIENCE OF ENVIRONMENTAL FLOW

Tharme (1996, 2003, 2008) has done a thorough scanning of the present and past evolution of environmental flow assessment on a global perspective. Following is a short summary of the origin of the environmental flow concept.

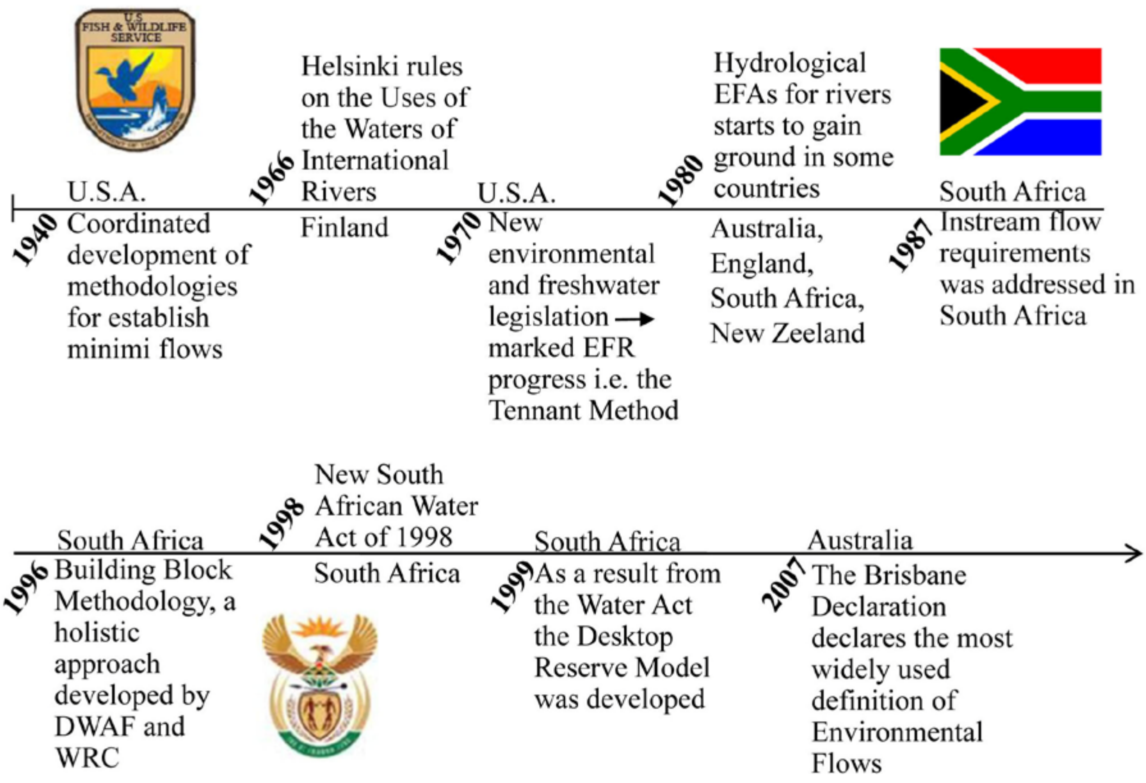


Figure 3.1. The major milestones in the development of environmental flows and the desktop reserve model. Department of Water Affairs (DWA), Water Research Commission (WRC) (Author's figure from Tharme, 2003; Brisbane Declaration, 2007).

The evolution of the science of environmental flow started in the western U.S.A. in the 1940s with the first *ad hoc* methods (Arthington *et al*, 2004). The awareness that reduced river flow was linked to reduced fish species lead to a coordinated development for establishing minimum flows. It took approximately thirty years before more formally documented techniques were developed in the 1970s. In 1976 Donald L. Tennant presents his findings after years of detailed river studies in northern U.S.A. The *Tennant Method* is today used in many countries including southern Sweden (pers. comment Jan Grosen). In Australia, England, New Zealand and South Africa the concept did not gain ground until 1980s, and later in e.g. Brazil, Czech Republic, Japan and Portugal (Tharme, 2003). Other parts of the world (e.g. Eastern Europe, Latin America, Africa, and Asia) appear according to Tharme to be "poorly advanced in the field". Figure 3.1 summarizes the major milestones in the evolution of environmental flow with special focus on the Desktop Reserve model and South Africa.

A global survey done by Moore (2004) shows that many terms are used to describe the *environmental flows* concept. The study showed that the three most common terms used were: *environmental flow*, *minimum flow* and *instream flow requirements*. This thesis will throughout use the word environmental flow as it is the most widely used term. It should however be mentioned that in South Africa the term environmental water requirements (or the ecological reserve) is used for what in this thesis is referred to as the environmental flow requirements.

3.2 LEGISLATION AND POLICY ON ENVIRONMENTAL FLOW

Provision of environmental flows is in many ways a political question, particularly if the river basin stretches over countries. The upstream users and the downstream users must both contribute with their shared part to the environmental flow. The environmental flow outlet must not be regarded as an extra resource for e.g. irrigation for the downstream users and should be allowed to reach the estuary where it plays a vital ecological role. This is one reason why the implementation of environmental flows is difficult and why the water policy is highly important.

3.2.1 Global legislation on environmental sustainability

In Helsinki, Finland, 1966 the Helsinki rules on the Uses of the Waters of International Rivers was adopted by the International Law Associations at the 52nd conference. Article IV-V outlines the basic principle: "What is a reasonable or equitable share of the resource is to be determined in the light of all the relevant factors in each particular case." Some listed relevant factors which are to be considered (but not limited to) are: the geography, hydrology, climate, past and present utilization, economic and social needs, and availability of other resources. (International Law Association, 1966). This highlights the fact that all water resource issues and problems cannot be solved by one universal solution, all unique factors must be taken into consideration. Chapter 18 of *Agenda 21* adopted at the Rio Conference in 1992 states some important agreements about the protection of the quality and supply of freshwater resources; they can be seen in Box 3. Agenda 21 is however not a law in a strict sense. According to Iza (2004) the United Nations convention on the Law of Non-navigational Uses of International Watercourses – UN Convention (UN General Assembly 21 May 1997) are of relevance to environmental flows. It is the only global agreement that addresses rivers in purposes other than navigation. The cornerstones of the Convention are the regulations to use international watercourses in an "equitable and reasonable manner" and "the prevention of harm to other riparian states" (Forslund, 2010).

Box 3: Important parts from Chapter 18 of Agenda 21 of the Rio Conference of 1992

> 18.2 "…adequate supplies of water of good quality are maintained for the entire population of this planet, while preserving the hydrological, biological and chemical functions of ecosystems…"
>
> 18.7 The overall objective is to satisfy the freshwater needs of all countries for their sustainable development.
>
> 18.8 "Integrated water resources management is based on the perception of water as an integral part of the ecosystem, a natural resource and a social and economic good, whose quantity and quality determine the nature of its utilization. To this end, water resources have to be protected, taking into account the functioning of aquatic ecosystems and the perenniality of the resource, in order to satisfy and reconcile needs for water in human activities…."

The Millennium Development Goals (MDGs) is a global agreement to cut the world's poverty in half by 2015 with eight development goals. Goal 7 "Ensure Environmental Sustainability" is focusing on how to reduce the loss of environmental and biodiversity resources. One indicator is the proportion of population with access to an improved water source (UNDP, 2006). According to Anna Forslund *et al.* (2009) one major problem with the MDGs is that it is this separate environmental target as the ecosystem services are crucial for all of the eight MDGs. Among the goals, number seven is the least clearly articulated one, which causes difficulties in monitoring the progress on environmental sustainability. Forslund *et al.* (2009, Table 6 page 42) give examples on the linkages between environmental flows and all the eight MDGs, which could be of interest for more curious readers.

In Europe the Water Framework Directive (WFD) (2000/60/EC) came into force in 2000. The overall objective is to achieve a "good status" to year 2015, or at latest year 2027 for all surface and groundwater. It is based on two classification systems: good ecological status and good chemical status. Setting environmental flows is a key step in achieving "good status" (Dyson *et al*, 2008). The European model is based on river basins and not administrative or political borders, and Europe has therefore been divided into water districts. To achieve a good status all river basins must set out a plan for how the objectives for the river basin are to be reached within the limited timeframe (European Union, 1995-2010).

3.2.2 Sweden's work with Environmental Flows

The Water Framework Directive has been implemented in Sweden through the Swedish Environmental Code (1998:808) and Ordinance (2004:660) for Water Management. The work is based on a river basin management plan, where the water resources ecosystem, social and economical values are taken into account. The results from the work are continuously reported back to the European Union.

The term environmental flow is not widely used or applied in Sweden (pers. comment Lars Degerman). Only two counties (of twenty-one) have decided on general minimum required water flows. Skåne County in southern Sweden has implemented two levels of minimum allowed water flows. The first level is for watercourses that have a special protection value: the minimum water flow is set to 30% of mean annual flow. The level is based on Tennant (1976) studies (Section 3.5). Watercourses with no special protection value are recommended to have at least 25 l/s per meter stream width (pers. comment Jan Grosen).

Many of the regulated stream flows in Sweden do not even have a minimum required flow. This is partly because the water-rights legislation is older than the Environmental Code. In new legislations as a rule of thumb, 5% of the production value is reserved for environmental purposes. This can roughly be estimated with 5% of the mean annual discharge. However, a hydropower producer is required to set aside up to 20% of the production value without getting any compensation if it can be motivated by ecological benefits, mainly regarding the production of migrating fish.

Degerman (pers. comment) gives one possible reason to the poor work: the Swedish hydropower industry has a very strong interest and control over the watercourses. Another reason can be that Sweden seldom experiences severe droughts.

3.2.3 South African National Water Act

The South African National Water Act (No. 36 of 1998) (Department of Water Affairs, South Africa) is based on 28 principles and objectives. Part 3 of the Act declares that water reserves consist of two parts; the basic human needs reserve and the ecological reserve. The ecological reserve relates to the water required to protect the aquatic ecosystems, and includes both the quantity and quality of the resource. The basic human needs include water for drinking, food preparation and personal hygiene. At present, this amount is calculated as a minimum of 25 liters per person per day. Another interesting principle is Principle 3 that declares that there shall be no ownership of water, only a right or an authorization for its use (Hirji & Davis, 2009). South Africa is the first country in the world to legislate the concept of “ecological reserve” as a right of law.

When the Water Act was implemented in South Africa 1998 the Department of Water Affairs (DWA) were required to determine the reserve for all, or a part of any significant water resource. This led to the development of a rapid method for assessing environmental flow requirements. It was recognized that this method could only provide environmental flow requirements with low accuracy and confidence as opposed to the higher confidence methods, which are time consuming and expensive to use. Instead it would be used to provide initial estimations of EFRs. This model was developed at the Institute for Water research in 1999 (Hughes & Munster) and the model became the so-called Desktop Reserve Model (DRM), originated from the BBM (Hughes & Hannart, 2003).

South Africa is leading in the work to legislate environmental flows; however they have experienced severe problems with implementing the concept in reality. None of the calculated environmental flows have been fully implemented up to date, although dams are being operated to release parts of the environmental flows (pers. comm. Estelle van Niekerk).

3.2.4 Environmental flows in Mozambique

Environmental flows have been discussed for approximately 20 years in Mozambique (pers. comm. Alvaro Vaz). It started with discussions about minimum flows. Today the discussion is about the importance of variability and maintenance of the natural flow regime. To perform holistic environmental flow methodologies such as the BBM is very complicated. Mozambique also does not have the expertise to collect all the necessary data which may span over many seasons. Apart from being a time consuming operation, using the BBM can also be a very expensive exercise (pers. comm. Alvaro Vaz).

Box 4. The Cahora Bassa Dam and Mphanda Nkuwa Dam in Zambezi River (WWF, 2004).

> Cahora Bassa Dam is a large dam used for hydropower in Mozambique. The environmental releases from the dam are only specified through a minimum flow requirement without any restrictions on the variability of these flows. The Zambezi delta below the dam does however need the high flows and this probably was the reason for the recent reduction in fish and shrimp catches. However, the banks and floodplains of the Zambezi River below the Cahora Bassa that used to be seasonal flooded are now being inhabited by the increased population resulting in a situation with a high risk of being flooded. A new dam, Mphanda Nkuwa Dam, is planned just 65 km downstream of Cahora Bassa Dam. There is a risk of increasing the environmental problems with the likely result of even lower floods and higher base flows in the lower Zambezi River with this new dam. The operating practice would cause the daily fluctuations in the river levels downstream to vary between 0.5 m to 2.8 m. The banks downstream could be seriously affected by these daily mini-floods with increased erosion as a result. Fish and numerous invertebrate species may disappear, either through the floods or habitat loss.

In the large regulated rivers that Mozambique shares with its neighbors, such as the Zambezi, Incomati and Limpopo Rivers, there is a large need to consider environmental flows (Box 4). For example, the Limpopo River has suffered decreased low flows during the dry season for many years, mainly because South Africa uses a lot of water for irrigation. Mozambique is currently in a process to reach a future agreement with its neighbors on sharing the water resources in Limpopo River in which environmental flows will be one component. For the Incomati River such agreement was established in 2002 between the three countries of South Africa, Mozambique and Swaziland. In this agreement the three countries agreed upon a minimum flow for the ecological reserve at about 5 % of mean annual discharge.

The water sector in Mozambique has a legal framework consisting of five major parts: National Water Law (1991), National Water Policy (1995, revised in 2007), Water Tariff Policy (1998), National Water Resources Management Strategy (2007) and the Regulation of Licenses and Concessions of Water (2007) (Sweco, 2010). Compared to South Africa environmental flows are not explicitly implemented into their legal framework.

3.3 DIFFERENT CATEGORIES OF ENVIRONMENTAL FLOW METHODOLOGIES

There is no single best way to do an environmental flow assessment. The choice of methodology depends on the availability of resources, i.e. data, time, funds etc. The major criteria for determining environmental flows should include the conservation of the variability of the natural flow. The timing of the environmental flows is complicated by the lack of understanding of the relationship between river flows and river ecology (Smakhtin, 2008) as well as uncertainties in the estimation of the hydrology. A database of various methodologies for environmental flow assessment, established in 2003, contains useful information on 134 methodologies with key references. This database is a valuable source of different environmental methodologies. The methodologies can be sorted by type, region or country where they have been applied. The major findings from the review process are presented in Tharme (2003).

There are four categories of environmental flow methodologies, which are recognized by most scientists in the environmental flow field. These four levels are listed in Table 3.1.

Table 3.2. The four significant different types of environmental flow methodologies are presented here (e.g. Tharme, 2008).

Environmental Flow Methodology	**Description**
Hydrological (Desktop Estimates, Look Up Table)	This is a simple and rapid method that uses hydrological data to derive the environmental flow requirement. A "minimum flow" often represents the flow intended to maintain the recommended river condition. Hydrological methodologies are generally used for the planning level and have been applied widely, both in developed and developing countries. The *Tennant Method* is the most widely used hydrological method.
Hydraulic Rating (Rapid Determinations)	These type of methodologies measure changes in various single river hydraulic variables (e.g. depth and velocity) to develop a simple relationship between biota habitat availability and river flow. A common methodology is the *Wetted Perimeter Method*, developed in Australia.
Habitat Simulation (Habitat Rating, Expert Panels, Intermediate)	The Habitat Simulation methodology provides links between discharge and available habitat conditions. It uses key target biota to predict habitat discharge curves or habitat time and exceedence services. *PHABSIM*, developed in U.S.A. is the most commonly applied methodology.
Holistic (Holistic Approaches, Frameworks, Comprehensive)	In a holistic approach all important flow characteristics (high floods, base flows etc.) are identified. These methodologies incorporate hydrological, hydraulic and habitat simulation models. The *Building Block Methodology* (BBM) is a holistic methodology and was developed in South Africa.

A number of hybrid categories exist that consist of bits and pieces of the four main methodologies. Some methodologies are entirely based on expert judgment with others using alternative approaches (see Tharme 1996 for examples).

Tharme (2003) has listed all the different methodologies for estimating the environmental flow requirements used worldwide. The distribution between the methodologies is presented in Figure 3.2 below.

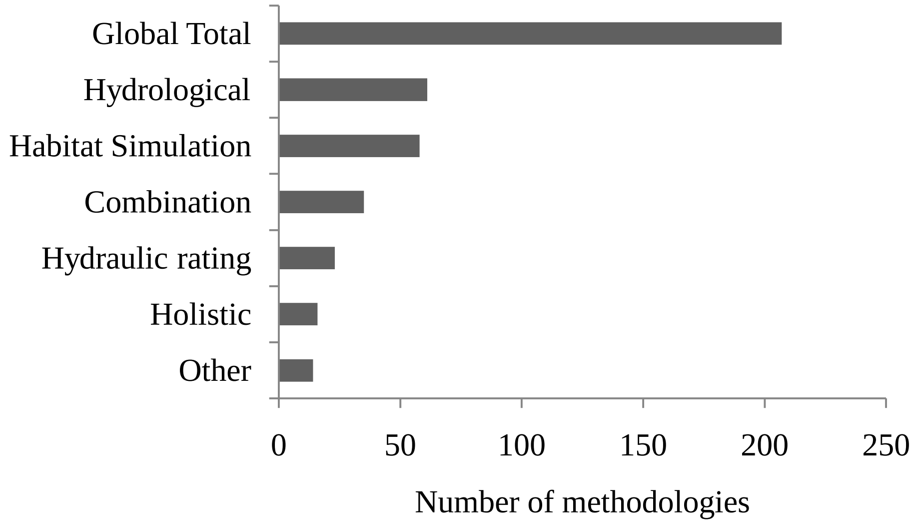


Figure 3.2. Number of environmental flow methodologies of each type and their proportion to the global total of 207 methodologies (data from Tharme, 2003).

This thesis will mainly focus on the hydrological methods (Figure 3.2). This methodology represents 29,5 % of all methodologies. In total South Africa stands for 10% of the 207 methodologies. They are distributed between the different types as follows:

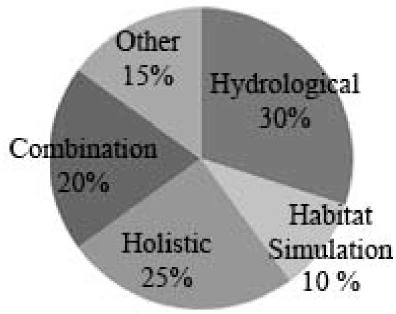


Figure 3.3. Relative percentage of different types of environmental flow methodologies used in South Africa. Notice that there are no hydraulic rating methodologies recorded (data from Tharme, 2003).

3.4 HOLISTIC METHODOLOGIES

A number of holistic approaches are used in South Africa. Apart from the Building Block Methodology described in more detail in the next section, there are also the well known and much used Habitat Flow Stressor Response (HFSR) and the Downstream Response to Imposed Flow Transformations (DRIFT) (Hughes & Louw, 2010) methodologies. The flow stressor response method was developed using Building Block Methodology as basis, and has been applied to about 10 advanced environmental flow studies during the past five years (Hirji & Davis, 2009).

3.4.1 Building Block Methodology (BBM)

The issue of instream flow requirements (assessments) for river maintenance was first addressed in South Africa in the mid-1980s. The South African Department of Water Affairs

(DWA) policy at this time was to develop a new way of managing water resources. There was growing recognition that a river ecosystem was not a competitor for the resource, but it was actually the resource itself. At this time the holistic method that was used for environmental flows determination was the Instream Flow Incremental Methodology (IFIM) developed in U.S.A. This method, as most methods developed in U.S.A., focused on specific aquatic species, which was not relevant for South Africa where the focus was on the management of complete river ecosystems. At that time the government had no structure for defining the desired future condition of a river, scientists were therefore asked to recommend and define such a condition and the corresponding flow (King *et al.*, 2000; King & Louw, 1998, King & Brown, 2010). The approach originating from this became the Building Block Methodology (BBM) (Tharme & King, 1998). Between 1991 and 1996 the BBM were used in workshops for 9 African rivers and 6Australian rivers (in Australia the method is called "The Holistic Method"). The principles of the BBM played a major role when the new South African Water Law was established in 1998.

The BBM method is based on the assumption that some flows (timing, duration and size) are more critical for ecological processes than others. Figure 2.1 shows some important flow characteristics and Figure 3.4 shows a natural river profile and the corresponding environmental flow requirement.

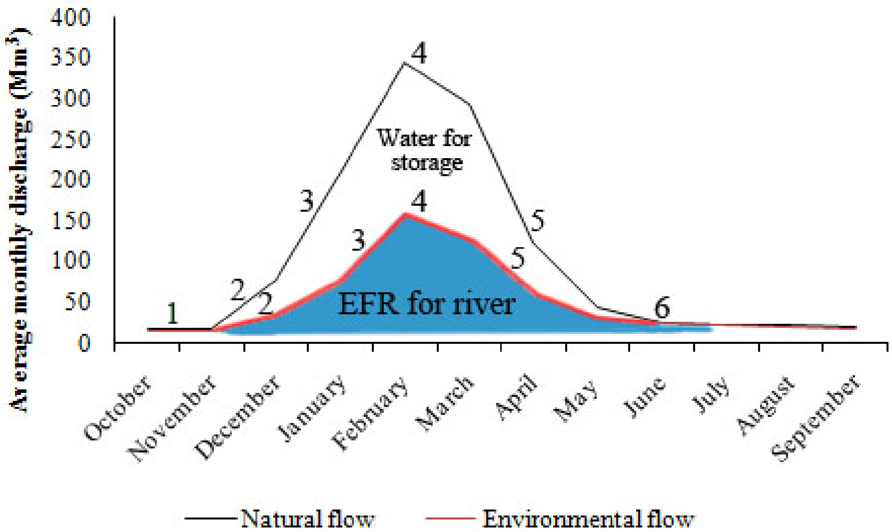


Figure 3.4. A river's natural flow regime should be kept when the river is modified. Features 1 and 6 shows the perenniality of the river, which should be retained when modified. 2,4 and 5 shows the difference between wet-season and dry-season baseflows, which also should be retained. Feature 3 may recognize the timing of the first major flood (author's figure from King & Louw, 1998).

The BBM identifies these critical flows and describes them in terms of their magnitude, duration, timing and frequency. The critical flows are identified by analyzing various components of the river ecosystem, such as the riparian vegetation, invertebrate and fish species. These flows are collated to represent the environmental flows according to the required, requested or desired ecological status of the river.

3.5 HYDROLOGICAL METHODS

The most simple environmental flow methodologies are the hydrological methods. They are often referred to as desktop models and rely primarily on the use of hydrological data, usually in the form of historical flow records, for making EFRs (King *et al.*, 2008). The results are often presented as a minimum required flow to maintain the ecological status at some acceptable level. There are numerous methodologies used in Southern Africa; Desktop Estimate, Rapid Reserve Determination, Flow Duration Curves percentiles (FDCs), Range of Variability approach (RVA), VHI, BWE, Ecotype-based Modified Tennant Method (Tharme, 2003).

The Tennant Method (or Montana Method) and de Range of Variability Approach (RVA), both developed in the U.S.A., are the most frequent used on a global perspective (Tharme, 2008). The Tennant Method differs from most other hydrological methodologies because it included expert opinions and detailed field studies when it was developed. D. L. Tennant (1976) presents his findings as follows:

- 10% of the average flow is a minimum flow recommended to sustain short-term survival habitat for most aquatic life forms;
- 30% is recommended as a base flow to sustain good survival conditions for most aquatic forms and general recreations; and
- 60% provides excellent to outstanding habitat for most aquatic life forms and for the majority of recreational uses

The recommended percentage of natural flow regime may also be varied during the seasons to satisfy the need during more sensitive times such as while fish is spawning.

The RVA is a rather new methodology. It derives from the aquatic ecology theory that emphasizes the importance of hydrological variability and its associated characteristics (indices) of magnitude, timing, frequency, duration, and rate of change of discharge (Poff *et al.*, 1998). It uses 32 hydrological parameters derived from long-term daily flow records as indicators of hydrologic alteration (Richter *et al.,* 1997). Another common hydrological methodology is the Flow Duration Curve Analysis (FDCA). Flow durations curves (FDCs) display the relationship between discharge and the percentage of time that it is exceeded.

3.5.1 Desktop Reserve Model (DRM)

The Desktop Reserve Model was developed in, and for South Africa by Hughes & Hannart (2003), to provide a quick low-confidence estimate of the environmental flow requirements. This model has gained application in other southern African countries, including Swaziland, Zimbabwe, Mozambique and Tanzania. It has also been applied to a river basin in Sri Lanka (Smakhtin & Weragala, 2005).

The Desktop Reserve Model is a hydrological model and one of the inputs to the model is generally the naturalized monthly flow data. Since the DRM uses the basic concepts and principles of the BBM it also employs the concept of different building blocks (BBs). The BBs are different components of flow, that when combined comprise a flow regime that intends to maintain a river in a recommended ecological class. The basis of the model is to establish the parameters for *baseflow separation* of the natural (or reference) monthly flow, which results in separating the total flow into high flows and low flows (Hughes, 2005). The flow building blocks in the Desktop Reserve Model comprise of low and high flows, during "normal years" and "drought years". The flow in normal years is referred to as *maintenance flow* and the flow in drought years is referred to as *drought flow*. The actual frequency of occurrence of "maintenance years" depends on the variability of the flow regime of the natural flow record. The Desktop Reserve Model provides estimates of these building blocks for each month of the year (Kashaigili *et al.*, 2007). The total maintenance flow comprises of the maintenance low flows and the maintenance high flows. The result from the DRM is the total environmental flow and it is presented as a fixed monthly percentage of the MAR (.tab-file), as well as monthly assurance rules (.rul-file) and as time series monthly flows (.mrv-file).

The flow variability plays a major role in the determination of environmental flows. Within the model two measures of hydrological variability are used; the Hydrological Index (CVB) and the Base Flow Index (BFI). These parameters are based on the flow duration curve characteristics of the natural flow regime (Hughes, 2005). The first index (CVB) is mainly a reflection of climatic variability (cycles of wet and dry periods). It is calculated from the average coefficient of variation (CV) (Standard Deviation/Mean) for the three main wet season months and the three main dry season months. The CVB does not satisfactorily reflect the short term variability (within a month or a season) and a second index is therefore required for this.

This index of baseflow (BFI) is the proportion of total flow that occurs as baseflow in the river. The BFI is closely associated with the runoff generation processes that dominate in the catchment of the river. The BFI varies between 0-1, and rivers with BFI close to 1 have less variability than those with a value close to 0 (Kashaigili, *et al*, 2007; Hughes & Hannart, 2003). BFI indicates the influence of soil and geology on river flows, and is important for low flow studies. Rivers with a high BFI are perennial, while rivers with low BFI values will have flows only for limited periods (seasonal). The baseflow separation is carried out on the full natural monthly time series using the following approach:

The relationship between Q75 (the flow equalled or exceeded 75% of the time) based on monthly and daily data can be assumed to apply:

$$Q75D = 0.89 * Q75M - 0.0099 \quad (1)$$

Where Q75D and Q75M are the 75% percentiles of the daily and monthly flow duration curve. Further on can the relationship between BFI and Q75D be considered applicable:

$$BFI = 0.832 * Q75D + 0.272 - 0.006 * T0 \quad (2)$$

Where T0 is the percentage number of months with zero flow (Hughes & Münster, 1999).

Equation 1 and 2 was developed for the original version of the Desktop Reserve Model. In the new version of the model a baseflow separation is carried out on the full natural monthly time series using the following approach:

$$q_m = \propto q_{m-1} + \beta(1 + \alpha)(Q_m - Q_{m-1}) \quad (3)$$

$$QB_m = Q_m - q_m \quad (4)$$

Where Q is the total flow, q_m high-flow component, QB_m baseflow component, *m* month, and α, β are the separation parameters. The BFI is calculated from the ratio of the mean annual baseflow to the mean annual total flow. The separation parameters are based on monthly time series, and regionalised values for α and β are available for the whole of South Africa (Hughes & Hannart , 2003).

The CV average divided by the BFI gives a hydrological index CVB which the model uses to calculate the environmental flow requirements (Mazvimavi *et al.*, 2007). The relationship between the CVB index and the maintenance low flow total as % natural MAR (MLIFR)

$$MLIFR = LP4 + (LP1xLP2)/(CVB^{LP3})^{(1-LP1)} \quad (5)$$

LP1, LP2, LP3 and LP4 are parameters with fixed values based on the ecological category (A-D) (Hughes & Hannart, 2003).

In semi-arid regions, most of the high flows are due to isolated events which increase the variability of flows. In the Desktop Reserve Model it is therefore assumed that the EFR for high flows increases with increasing flow variability. The equation used for estimating maintenance high flow total as % natural MAR (MHIFR)

$$MHIFR = \gamma * HP2 + HP3 \quad (6)$$

If CVB > 15 then

$$MHIFR = (\gamma * HP2 + HP3) + (CVB - 15) * HP4 \quad (7)$$

where HP2, HP3 and HP4 are parameters which depend on the desired environmental class. γ is a function of CVB and another parameter HP1 (Mazvimavi *et al.* 2007).

The model has pre-calibrated regionalized monthly distribution curves. It is a 2-D array attribute that contains the default values for additional parameters of the Desktop Reserve Model. The curves were calibrated for a specific region and so far only curves for South Africa and parts of Mozambique are available. It is however possible to calibrate the curves manually for other regions. The reliability of these new curves will however depend on the reliability and availability of previous high level EFRs in hydrological similar catchments.

3.6 PRESENT ECOLOGICAL STATUS

Quantifying the environmental flow for rivers involves determining the water quantity and quality requirements that will ensure that they are sustained in a pre-determined condition. To determine this condition the first step is to determine the present ecological status of the river. The Desktop Reserve Model requires a recommended ecological category (REC) for the EFR site where the model is applied. The process of determining the present ecological status (PES) is called *Eco Classification*. The objective of Eco Classification is to decide the ecological state of various components of a river relative to its natural (pristine) condition. The components are drivers (physic-chemical, geomorphology and hydrology) and biological responses (fish, riparian vegetation and aquatic invertebrates). The ecological state of the drivers and responses are then integrated using rule-based models to form the Ecological Status, or simpler the Eco Status. The Eco Classification process is a necessary part of any environmental flow requirement method (Kleynhans & Louw, 2007).

The Eco Status is defined by Kleynhans and Louw (2007):

"The totality of the features and characteristics of the river and its riparian areas that bear upon its ability to support an appropriate natural flora and fauna and its capacity to provide a variety of goods and services."

Several methods for determining the Eco Status have been developed and they vary from desktop level to comprehensive detailed methods. Depending on the type of environmental flow methodology (level of reserve determination) used, the appropriate Eco Status method is chosen.

The Eco Status classification system in South Africa is built up of six main levels (A-F) where "A rivers" are largely unmodified (reference conditions) and "F rivers" have modifications which have caused an almost complete loss of natural habitat and biota (Table 3.2). The river categories E and F can describe the present ecological status of the river, but is never used as a recommended ecological category because the philosophy is that no river should be allowed to degrade to such an extent. The recommended ecological category is a target level of the desired state of the river, based on the present ecological status and the ecological importance and sensitivity (EIS) (King *et al.*, 2008) as well as the future policy for managing this river. This thesis will only focus on the present ecological status and will therefore not go into detail of the recommended ecological category or the ecological importance and sensitivity (see e.g. Kleynhans and Louw (2007) for this).

Table 3.3. Ecological class for ecological status components (modified from Kleynhans & Louw, 2007).

Ecological Class	Description
A	Unmodified, largely natural
B	Largely natural with few modifications. A small change in natural habitats and biota may have taken place but the ecosystem functions are essentially unchanged.
C	Moderately modified. A loss and change of natural habitat and biota have occurred, but the basic ecosystem functions are still predominantly unchanged.
D	Largely modified. A large loss of natural habitat, biota and basic ecosystem functions has occurred.
E	Seriously modified. The loss of natural habitat, biota and basic ecosystem functions is extensive.
F	Critically/Extremely modified. Modifications have reached a critical level and the system has been modified completely with an almost complete loss of natural habitat and biota. In the worst instances the basic ecosystem functions have been destroyed and the changes are irreversible.

The A to F scale is however a continuum (Figure 3.5) and the boundaries between the categories are not fixed.

Figure 3.5. The Ecological Categories presented on a continuum. The boundary categories are denoted A/B, B/C and so on (figure by author).

In South Africa the responsibility of the management category of a river lies with the Minister in charge of The Department of Water Affairs (DWA) after consultation with stakeholders in the area (Hughes, 2001). The recommended ecological category can be set at the same level as the present ecological status. Normally it is some level above but seldom below as this would lead to river degradation instead of improvement. It is assumed that the total environmental flow requirements for a specific river decrease when the ecological status changes from A to D (Hughes & Hannart, 2003).

4 STUDY AREA

4.1 BUZI RIVER BASIN

4.1.1 Climate and hydrology

The Buzi River basin is located in the central part of Mozambique (Figure 4.3). It borders the Pungwe River basin to the north and the Save River basin to the south. The Eastern Highlands in Zimbabwe are located along the border of Mozambique. Southwest of town Chimoio are the Chimanimani Mountains with Mt. Binga (2436m) Mozambique's highest peak located in the Buzi River basin. The total area of the basin is 28980 km^2 and approximately 3850 km^2 (13%) of the Buzi River catchment is located in Zimbabwe and 25130 km^2 (87%) in Mozambique. The mean annual precipitation (MAP) decreases from 1800 to 1200 mm/yr in the northern portion of the Eastern highlands, 1200 to 1100 mm/yr in southern part of the Eastern Highlands and 1100 to 900 mm/yr in the central and western parts. The altitude decreases from approximately 1800 meters above sea level (m a.s.l.) in the highlands, to 600 m a.s.l. at Chicamba Dam and 80 m a.s.l. at the point where Buzi River and Revue River meets.

The natural mean annual runoff varies from approximately 300-800 mm/year in the eastern highlands. The middle basins have a MAR that is approximately 500 mm/yr and in the lowland part of the river basin the MAR is around 200-300 mm/yr.

The river basin consists of three main rivers Buzi, Lucite and Revue and it is divided into 12 sub-basins (Table 4.1 and Figure 4.3).

Table 4.4. Area, mean annual precipitation (MAP) and mean annual evaporation (MAE) divided on the 12 sub-basins in Buzi River basin (Sweco, working material, August 2010).

Main River	Sub-basin	Area [km^2]	MAP [mm]	MAE [mm]
BUZI	Buzi Zim	535.30	1200	~ 900
	Mossurize Zim	786.13	1200	~ 900
	Upper Buzi	4844.60	1100	~ 1200
	Middle Buzi	4331.65	900	~ 1300
	Lower Buzi	3258.37	900	~ 1400
	Total:	13756.05	1000	~ 1250
LUCITE	Rusitu Zim	969.10	1300	~ 900
	Upper Lucite	3884.77	1200	~ 1200
	Lower Lucite	1892.00	1000	~ 1400
	Total:	6745.87	1160	~ 1210
REVUE	Zonde Zim	379.01	1300	~ 900
	Upper Revue	2462.34	1200	~ 1000
	Middle Revue	2463.45	1100	~ 1050
	Lower Revue	3138.61	1100	~ 1400
	Total:	8443.41	1140	~ 1160

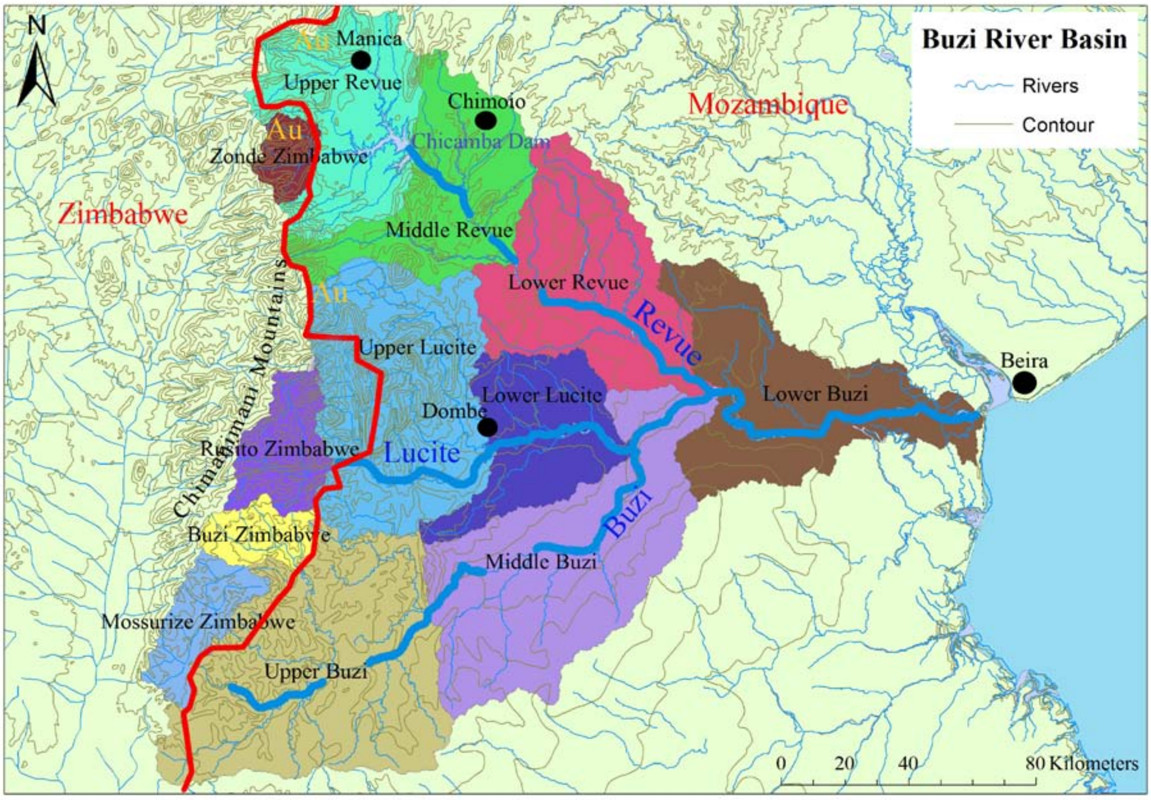


Figure 4.3. Buzi River basin divided into twelve sub-basins. Revue, Lucite and Buzi River are marked with a wider blue line which is not proportional to their real size.

The coastal and inland areas of the Buzi River basin experience regular flooding. The most recent floods were in 2000, 2007, 2008 and in 2010. The flooding is either caused by intense rainfall upstream or surges from cyclones (Sweco, working material, August 2010).

4.1.2 Area description and water users

Revue River is the more developed of the three tributaries and flows through the Manica province. It has the large Chicamba Dam (Figure 4.4 and 4.5) operated by "Electricidade de Mocambique" (EDM). Chicamba Dam was built in 1956 and upgraded in 1968 and is mainly used for hydropower. It serves the central region of Mozambique with electricity, sometimes even parts of Zimbabwe. It also supplies water to the cities of Chimoio and Villa Manica. The dam has a maximum storage capacity of 2020 Mm^3 and the surface area corresponding to that volume is 120 km^2 (Boa Ventura pers. comm.) The dam is also an important site for local fishermen.

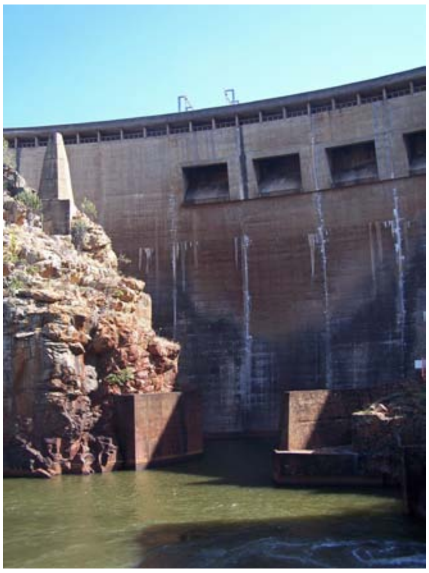


Figure 4.4. Chicamba Dam from below. Two turbines can produce a maximum of 19.2MW each (Photo Lovisa Lagerblad).

Figure 4.5. The water level of the dam was at the time of visit 613 meter above sea level. The maximum water level is 625 m a.s.l. (Photo Lovisa Lagerblad).

Another dam is located downstream of the Chicamba Dam, the Mavuzi Dam. It is also operated by EDM and uses the regulated flows from Chicamba to produce hydropower. Mavuzi Dam does not have any large weir, the hydropower is produced through a 1.6 m wide pipe with 160 m head.

The Revue River is also used for irrigation, mainly sugarcanes, maize, mango and banana plantations. There are several companies that operate in the Buzi sub-basins, most of them are located in the Upper and Middle Revue, except from the Buzi Company that has a sugarcane plantation in the Lower Buzi. A couple of decades ago the area had several tobacco plantations, but almost all of them disappeared during the tobacco crisis. Recently Jatropha (a small tree that produces a seed used for biofuel) plantations are starting to pop up in the Manica region. A British company, SunBiofuels, planted 1000 ha in 2009 just outside Chimoio and is planning for a total of 15000 ha (SunBiofuels, 2009).

Artisanal gold mining, both illegal and legal, takes part in the eastern part of Upper Revue, close to the Zimbabwean border. The extent of the gold mining is not known, but thousands of people are involved (Eduardo Ndunguro pers. comm.). Artisanal gold mining constitutes a threat to both the environment and miners.

Figure 4.6. Illegal and legal artisanal gold mining in the Revue River affects the levels of sediments. This picture shows the river bank where the washing is taking place. Location S 18°52’52.80’’ E 32°51’11.21’’ (Photo Lovisa Lagerblad).

Figure 4.7. The illegal gold miners call themselves “garimpeiros” in Portuguese. This field close to Villa Manica opened in January 2010 and hosts hundreds of miners (Photo Stéphanie Nicolin).

The Lucite River is not as developed as Revue River. It has no large dams or weirs, but around the city of Dombe, mango and banana plantations are common. Sugar cane plantations for bio fuel are also common in the region, where Mozambique Principle Energy has a large plantation area.

The Buzi River is the least developed of the three rivers. The major cities along the river are Chibabava in Mozambique and Chipinge in Zimbabwe. Some of the areas in this section of the basin are very remote and difficult to access. People in this region are often small scale farmers that uses rain fed agriculture. This makes them very vulnerable for rainfall irregularities and the people in the region are in general poor. Irrigation development is an essential opportunity for the whole Buzi river basin, and therefore it is an important water resource (Sweco, 2008).

5 METHODOLOGY FOR CASE STUDY

In order to gain the necessary background information on applying the environmental flow methodology a literature study was performed. The result from the literature study is presented in Chapter 3. Information about the river basin was also collected for planning the field trip.

The following main tasks were undertaken:

- Investigate and collect information about the study area and select EFR sites.
- Undertake the field study to collect information about the water users and the present ecological state.
- Determine the present ecological state using the spreadsheet from Kleynhans (1996).
- Calculate the environmental flow requirements with the Desktop Reserve Model incorporated in SPATSIM.

5.1 FIELD STUDY

To decide on the present ecological state of the Buzi River basin, a four day field visit was conducted from June 15 to June 18, 2010. The field trip was during the dry season when the flow in the river was low. Mr. Antonio Melembe, a hydrologist from ARA-Centro in Beira, acted as guide and translator.

The places that were visited were selected based on accessibility by car and unique features. They were also selected because some of them had water users possible to affect the rivers' quantity, quality or timing of water.

During the field visit in situ interviews were performed orally. Some of them were more planned while others were spontaneous. The people that were interviewed that only spoke Portuguese were translated through Mr. Melembe to English.

At all sites were photos taken and the exact location was registered on a GPS.

5.1.1 Assessment of the present ecological status (PES)

To determine the present ecological status a procedure developed by Kleynhans (1996) was used. The procedure was developed for rapid desktop estimates. According to Kleynhans (pers. comm.) this method can be used even with very limited data, though the level of the study will be "rough and dirty". The result was linked to a level of confidence, from very low to high, based on the availability of information. The procedure used here was an Excel spreadsheet that was filled in after the field study was completed.

The methodology used through the spreadsheet to determine the PES, is based on an impact evaluation of instream habitat integrity and riparian habitat integrity. It also evaluates fish and macro invertebrates to describe the PES. Unfortunately, due to time and knowledge limitations, no information on biota was collected as part of this study. The instream and riparian habitat have different categories (Table 5.2) to analyze the PES, and were scored using the criteria shown in Table 5.1 and weighted (see brackets in Table 5.2) to produce the integrity score (Figure 5.1). The categories were rated from no impact (0) to critical impact (21-25) which is explained in Table 5.1 below. The two integrities were then weighted together to produce the overall river integrity. The overall river integrity by this step has an integrity score between 0-100. The integrity score was subsequently transformed into the ecological category (A to F). The transformation was done according to the listed categories in Figure 5.1. All the categories were assessed during field visit, even though some were complex and required expert input and more time to be evaluated.

Table 5.5. The categories of the riparian and instream habitat integrity were scored according to the level of impact (Kleynhans, 1996: pers. comm. Retha Stassen).

Rating system for integrity impact			
Impact	**None**	**Small**	**Moderate**
Score	0	1-5	6-10
Description	No traceable impact, or the modification is located in such a way that it has no impact on habitat quality, diversity, size and variability.	The modification is limited to very few localities and the impact on habitat quality, diversity, size and variability is also very small.	The modifications are present at a small number of localities and the impact on habitat quality, diversity, size and variability is limited.
Impact	**Large**	**Serious**	**Critical**
Score	11-15	16-20	21-25
Description	The modification is generally present with a clearly detrimental impact on habitat quality, diversity, size and variability. Large areas are, however, not influenced.	The modification is frequently present and the habitat quality, diversity, size and variability in almost the whole of the defined area is affected. Only small areas are not influenced.	The modification is present overall with a high intensity. The habitat quality, diversity, size and variability in almost the whole of the defined section are influenced detrimentally.

Graham and Louw (2008) have developed a manual for determination of habitat integrity. The manual is an illustrated photo guide that gives examples of different modification (e.g. hydrological, bed and bank, physic-chemical etc.). The guide illustrates how different rivers are rated based on their characteristics. This photo manual was used for assessing the present ecological status in Buzi River basin.

Table 5.6. This table shows what was analyzed during field visit to produce the present ecological state. The number next to the category is the criteria weights which the spreadsheet in excel automatically calculates.

Habitat Integrity	
Riparian (criteria weights)	**Instream (criteria weights)**
Vegetation decrease (13)	Water Abstraction (14)
Exotic vegetation (12)	Flow Modification (13)
Bank Erosion (14)	Bed Modification (13)
Channel Modification (12)	Channel Modification (13)
Water Abstraction (13)	Water Quality (14)
Inundation (11)	Inundation (10)
Flow Modification (12)	Exotic Macrophytes (9)
Water Quality (13)	Exotic Fauna (8)
	Solid Waste Disposal (6)
Total: 100	100

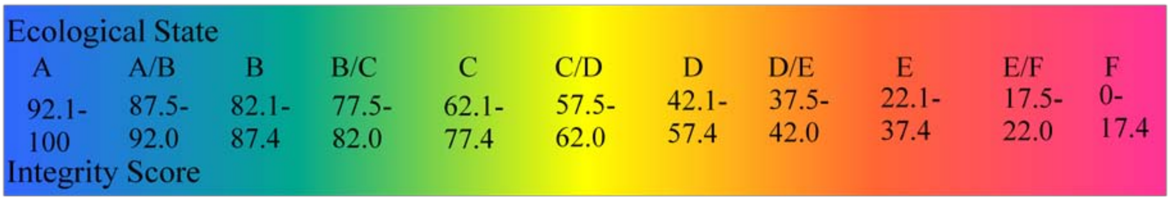


Figure 5.1. The Integrity Score was transformed into the ecological state through the correlation presented in this figure (data from Kleynhans, 1996, figure by author).

The excel spreadsheet used for this study can be found in Appendix B.

Information related to the ecological status was also collected through interviews with people who had local knowledge. Aerial surveys by Google earth providing rough information about land use and sedimentation were also analyzed to assist in the assessment of the PES.

5.1.2 Selecting environmental flow requirements (EFR) sites

The sites for environmental flow requirements were selected at the outlets of the sub-basins where natural flow records were available from the hydrological study on the Buzi basin. These sub-basins coincide to a great extent with the changing topography from the mountainous inland areas, to the very flat plains closer to the sea. In theory, an EFR site is required for every ecologically homogenous stretch in a river, and each resource unit should ideally have an EFR site. It is also recommended to have an EFR site at any planned future development, to monitor and mitigate the impact of any new developments (pers. comm. Estelle van Niekerk).

5.2 MODELLING THE ENVIRONMENTAL FLOW REQUIREMENTS WITH DESKTOP RESERVE MODEL

5.2.1 Hydrological data

The data needed for the Desktop Reserve Model was supplied by Mr. Olof Persson (Sweco, 2010), who was involved in the Buzi River Hydrological study. The Desktop Reserve Model requires runoff data as a monthly time series. As the length of the flow record used to set the EFR increases, confidence in the understanding of the long-term flow regime at the site increases, and therefore also in the EFR that will be calculated using this record. The runoff data used in this study was monthly data from year 1954 to 1999 modeled with PITMAN, which gives natural runoff data with a record length of 46 years. The assumption is that these records represent natural flow conditions and are therefore suitable to use with the desktop reserve model. The confidence level in the hydrological data is very low because of lack of flow gauging stations in the river. Consequently, the data was used and interpreted with great caution.

5.2.2 SPATSIM Spatial and Time Series Information Modelling Software

SPATSIM, the interface through which the Desktop Model is run, was developed by the Institute of Water Research and the Water Research Commission of South Africa (who also has the copyright). It has free licence and can be downloaded from internet and used by anyone. SPATSIM uses GIS map objects together with a programming language for creating and managing different types of hydrological and water resource information. The program has limited GIS facilities and also provides access to a wide range of other models and data analysis procedures. The program has five major model and data analysis tools:

1. General Hydrology Data Analysis Models
2. Catchment Rainfall-Runoff Models
3. Flood Models
4. Water Resource Systems Models
5. Ecological Reserve Models

The Desktop Reserve Model belongs under number five in the above list; Ecological Reserve Models. The SPATSIM model incorporates in total ten different reserve models, which will not be discussed here. If the reader is interested in gaining more information about these models, visit the online help manual available at Rhodes University webpage (Home > IWR > Hydrology > SPATSIM).

The Buzi River basin in Mozambique has characteristics similar to other river basins in South Africa, and the method is therefore expected to be useful in Mozambique. Hughes and Hannars (2003) recommended the use of the Desktop Method in southern Africa.

The SPATSIM version 2.7 was used for this project. This version incorporated monthly distribution curves (provided by Prof. Denis Hughes) for Mozambique for both wet and dry conditions. The wet curves were used in regions with mean annual precipitation (MAP) exceeded 1300mm/year. Where the MAP was between 1200-1100 mm/yr the model was run with both the wet and the dry curves and compared with the flow regime of the natural flow to select the most appropriate curve. Below 1000 mm/yr, the dry curves were used. The curves were developed based on the work done by Hughes (2005) in Northern Central Mozambique. The model was not adjusted for the Buzi River basin, but some preliminary checks were done to assure that the results were acceptable.

The calculated environmental flow requirements from SPATSIM were compared to the natural flow to assure that the EFR did not ask for more water than naturally flows in the river. This was done by simply subtracting the timeseries of EFR from the natural flow.

The result from the model is presented in million cubic meters (Mcm or Mm^3) monthly.

5.3 SENSITIVITY ANALYSIS OF DESKTOP RESERVE MODEL

This thesis focuses on the input uncertainty, because the confidence that can be achieved when modeling EFRs is highly dependent on the input uncertainty (Hughes & Louw, 2010). Furthermore one of the major obstacles with environmental flows is that the availability of input data is low and often of poor quality.

The Desktop Reserve Model is based on the relationship between hydrological variability and the required flow to achieve a recommended ecological category. The calculated EFRs are based mainly on high level reserve determinations in South African rivers where parameters were extrapolated from the relationships between flow and ecological response (Hughes & Louw, 2010). This study shows how the recommended (which is the same as the present ecological state in this instance) affects the calculated environmental flow.

6 RESULTS OF THE CASE STUDY

The environmental flow sites were selected based on the hydrological sub-basins and therefore situated at the outlet of every sub-basin. Five of the twelve EFR sites were analyzed in more detail to establish their present ecological status. The results from the Eco Classification shows that one of the EFR sites was at present ecological state (PES) of C, while the other four were at PES of B.

The environmental flow requirements were calculated for all the EFR sites for all categories A to C. The average EFR expressed as % of the natural MAR for a class A was found to be 57.1%, class A/B 46.8%, class B 37.2%, class B/C 30.7% and class C 23.9%.

This short summary of the results are described in more detail in the following sections. It should be remembered that all results should be treated as a first estimate, low-confidence answers and should be used with caution. However, these results are at present the best available estimates of the required EFR in the Buzi River, as well as the best available estimate of the present ecological state of the Buzi Basin, until more time and budget is spent to improve these results.

6.1 CHARACTERISTICS OF FLOW REGIMES

The inter-annual variation of the flows in Buzi River is very large (Figure 6.1 and Figure 6.2). The flows are seasonal with the wet season lasting December to May with generally the highest flows in February (Figure 6.3). The Buzi River is generally perennial. The natural monthly flow variation for the sub-basins are quite similar, therefore only two of them are presented in this result section and the other can be found in Appendix A.

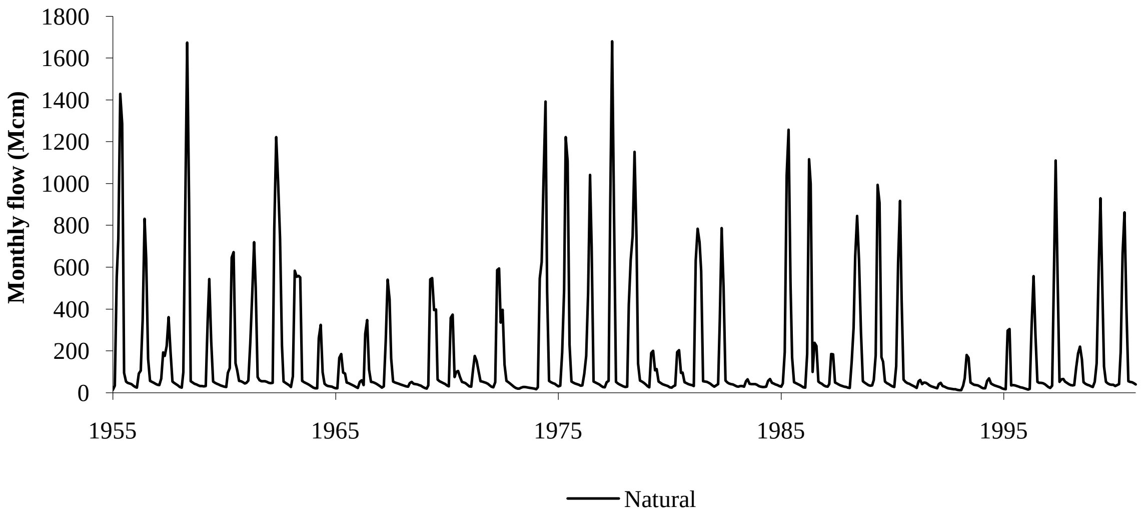


Figure 6.1. Simulated natural flows (Mm^3/month) for the last 45 years in the eastern part of the Buzi River basin (example from sub-basin Upper Lucite). The maximum flow for this time period was in February 1958 with a monthly flow of 1670 Mm^3 and in March 1977 with a flow of 1680 Mm^3. Several periods of droughts have been experienced, e.g. between 1991-1995.

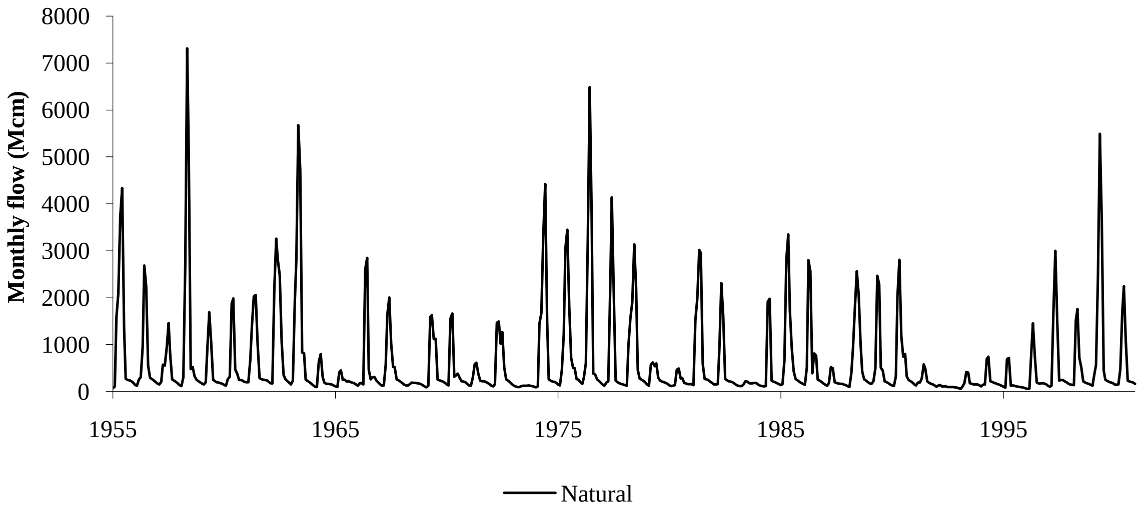


Figure 6.2. Simulated natural monthly flow variation (Mm^3/month) from the Lower Buzi which is the last sub-basin before the river mouths the Indian Ocean. The monthly flow axis scale differs from the Upper Lucite above because of the cumulative effect of more water in the lower river sections.

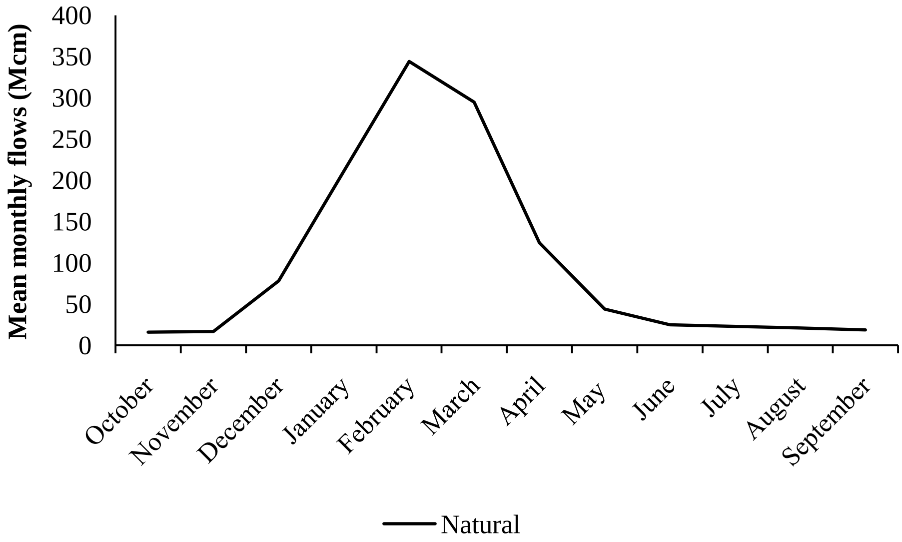


Figure 6.3. Wet season starts in December and ends in April/May and the dry season lasts from June to November. This seasonal distribution curve is a simulated average from 45years from the Upper Revue but the shape is representative of the whole basin's wet and dry season characteristics.

6.2 ENVIRONMENTAL FLOW REQUIREMENT SITES AND PRESENT ECOLOGICAL STATE

Twelve EFR sites were used in the study (Figure 6.4). The positions of the sites are listed in Appendix C. Only five of the twelve EFR sites have been investigated in detail to determine the present ecological status, and therefore only those five are presented in the following sections.

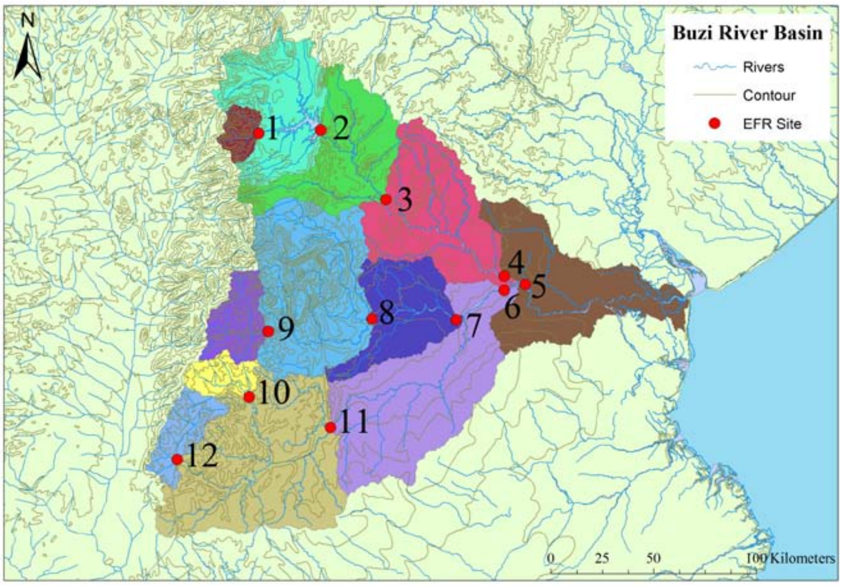


Figure 6.4. The Buzi River basin with its twelve sub-basins. The red dots marks the EFR sites used in this study. At site number 2-6 the present ecological state has been determined with the Kleynhans (1996) method. See Appendix C for the names and the GPS positions of the EFR sites.

6.2.1 Upper Revue

Figure 6.5. Bridge over Revue River just below the Chicamba Dam (Photo Lovisa Lagerblad).

Figure 6.6. View from the dam looking downstream of the Revue River and the bridge (Photo Lovisa Lagerblad).

The Upper Revue EFR site is located just below the Chicamba Dam (see Figure 4.3 and the red dot with number 2 in Figure 6.4) and at this site, the river is affected by the dam. The site is easily accessble by car. The Revue River is a major tributary of the Buzi River. The cumulative natural MAR at the EFR site is 1218 Mm^3 at the outlet of Upper Revue. The total catchment area (Upper Revue and Zonue Zim) is 2857.5 km^2. It is expected that the Chicamba Dam will accumulate most of the chemicals that are responsible for the water quality issues (Figure 6.7 and Figure 6.8) in the sediments.

The present ecological state derived from the Kleynhans (1996) procedure is presented in Table 6.1. The assessment scores can be seen in Appendix B. The main negative impacts on the Revue River at the EFR site are the following:

- Flow modification from Chicamba Dam affecting the natural river flow pattern
- Possible physico-chemical modifications such as water temperature and pH changes

Figure 6.7. Mercury is used for flocculating gold, this can pollute the water and the environment (Photo Lovisa Lagerblad).

Figure 6.8. A small tributary to the Revue River with increased sediment levels which causes the water to turn red (Photo Lovisa Lagerblad).

Table 6.7. The present ecological state of the instream and riparian habitat integrity at EFR site Upper Revue. The integrity score puts it in the C class.

Component	PES	Explanation
Instream Habitat Integrity	C	Hydrological flow modifications: changes in flow variability. Possible physico-chemical modifications: water temperature and pH changes, toxics from the pollution from mining. Longitudinal transport is reduced which leads to increased sediment and nutrient levels in the reservoir and decreased downstream.
Riparian Habitat Integrity	C	Hydrological modifications: frequency and seasonality change in large floods. Bank structure: mining upstream causing increased levels of sediment and bank erosion problems.
Present Ecological State	**C**	A small loss and change in natural habitats may have taken place. The erosion and increased sediment levels are the largest threats. The PES downstream the dam is assumed to be better than upstream due to the sedimentation in the dam that prevents pollutants from getting through.
Integrity Score	75.8	

6.2.2 Middle Revue

The site is located approximately 50 km downstream the Chicamba Dam in the Revue River, see red dot number 3 in Figure 6.4. The cumulative MAR at the EFR site is 1970 Mm^3 at the point of the outlet. The total catchment (Upper Revue, Zonue Zim and Middle Revue) area is 5330,5 km^2. The Chicamba Dam is the only weir affecting the site. The Revue flows mostly through wooded grasslands and grasslands. Uncontrolled deforestation is likely to be a problem in this region (Figure 6.9).

The present ecological state derived from the Kleynhans (1996) procedure is presented in Table 6.2. The assessment scores for the habitat integrity can be seen in Appendix B. The main negative impacts on the Revue River at the EWR site Middle Revue are the following:

- Bank erosion
- Increased sediment levels
- Flow modifications from Chicamba Dam

Table 6.8. The present ecological state of the instream and riparian habitat integrity at EFR site Middle Revue.

Component	PES	Explanation
Instream Habitat Integrity	B	The flow regime is affected by the Chicamba Dam but with less impact than upstream because of unregulated tributaries that contribute to the natural flow. Increased levels of sediments from natural and unnatural erosion.
Riparian Habitat Integrity	B	Decrease in bank stability will cause sedimentation and possible collapse of the river bank. Possible change in large floods.
Present Ecological State	**B**	A small loss and change in natural habitats may have taken place. The erosion and increased sedimentation levels are the largest threats.
Integrity Score	84.8	

Figure 6.9. Trees are cut down uncontrolled to produce coal. Trees stabilize the land and deforestation cause soil degradation and erosion problems (Photo Lovisa Lagerblad).

6.2.3 Lower Revue

The site is located just before Revue River and Buzi River meets, see red dot number 4 in Figure 6.4. The highway EN1 crosses the Revue River at this point. The cumulative MAR at the EFR site is 2524.9 Mm^3. The total catchment (Upper Revue, Zonue Zim, Middle Revue and Lower Revue) area is 8443.3 km^2.

The present ecological state derived from the Kleynhans (1996) procedure is presented in Table 6.3. The assessment scores for the habitat integrity can be seen in Appendix B.

Figure 6.10. The water at the EFR site Lower Revue was clear (Photo Lovisa Lagerblad).

Figure 6.11. Looking downstream from the EFR site. The water level was low at the time of visit (Photo Lovisa Lagerblad).

Table 6.9. The present ecological state of the instream and riparian habitat integrity at EFR site Lower Revue.

Component	PES	Explanation
Instream Habitat Integrity	B	Chicamba Dam and Mavuzi Dam have some impact on the flow. Settlements in the area might cause some minor pollution.
Riparian Habitat Integrity	B	Vegetation decrease in the area Small banana plantations on the river bank.
Present Ecological State	**B**	A small loss and change in natural habitats may have taken place. Deforestation along the river banks can cause increased erosion problems.
Integrity Score	84.4	

6.2.4 Lower Buzi

The Lower Buzi EFR site is located after the confluence of the Revue and Buzi rivers, see red dot number 5 in Figure 6.4. The cumulative MAR at the EFR site is 7093.3 Mm^3. The total catchment area is 25722 km^2.

Figure 6.12. Erosion can cause a collapse of the river bank and this house was destroyed by the last flood. The poles are placed to prevent more erosion and houses from getting caught by the river (Photo Lovisa Lagerblad).

The present ecological state derived from the Kleynhans (1996) procedure is presented in Table 6.4 below. The assessment scores for the habitat integrity can be seen in Appendix B.

Table 6.10. The present ecological state of the instream and riparian habitat integrity at EFR site Lower Buzi.

Component	PES	Explanation
Instream Habitat Integrity	B	The water quality in the river is affected from human settlements, agriculture, deforestation and gold mining. The water is however fairly good because of large amounts of almost pristine water from unaffected tributaries.
Riparian Habitat Integrity	B	Collapse of the river bank can result in a loss of both instream and riparian habitats.
Present Ecological State	**B**	A small loss and change in natural habitats may have taken place.
Integrity Score	86.5	

6.2.5 Middle Buzi

The EFR site Middle Buzi is located in Buzi River before Buzi River and Revue River meets, see red dot number 6 in Figure 6.4. The highway EN1 (see Figure 6.13) crosses the Buzi River at this point. The cumulative MAR at the EFR site is 4568.5 Mm^3. The total catchment area is 17243 km^2.

Figure 6.13. The EN1 road passing over at the EFR site. At the bridge pier closest in view is a water measurement scale (Photo Lovisa Lagerblad).

Figure 6.14. A young man collects reddish water at the EFR site (Photo Lovisa Lagerblad).

The present ecological state derived from the Kleynhans (1996) procedure is presented in Table 6.5 . The assessment scores for the habitat integrity can be seen in Appendix B.

Table 6.11. The present ecological state of the instream and riparian habitat integrity at EFR site Middle Buzi .

Component	PES	Explanation
Instream Habitat Integrity	B.	Water quality is the biggest problem at this EFR site with increased sediment levels from upstream erosion caused by mining.
Riparian Habitat Integrity	B	Some removal of indigenous riparian plants. Changes of water quality do also affect the habitat integrity.
Present Ecological State	**B**	A small loss and change in natural habitats may have taken place.
Integrity Score	86.4	

6.3 ENVIRONMENTAL FLOW REQUIREMENTS

6.3.1 Effects of hydrological regime on EFR

The equations (Section 3.5.1) used in the Desktop Reserve Model are constructed so that the proportion of the natural flow required for the EFR increases with increasing Base Flow Index (BFI). This correlation is true in the case study from Buzi River basin (Figure 6.15) which is based on the EFR sites evaluated in the Buzi River basin. A high Base Flow Index value (close to 1) indicates a river with less variability than those with a value close to 0. The BFI varies from 0.325-0.419 in the Buzi River basin. The difference between the highest EFR (highest percentage of the natural flow) and the lowest EFR (lowest percentage of the natural flow) within a specific class, is slightly larger for a higher class than a lower.

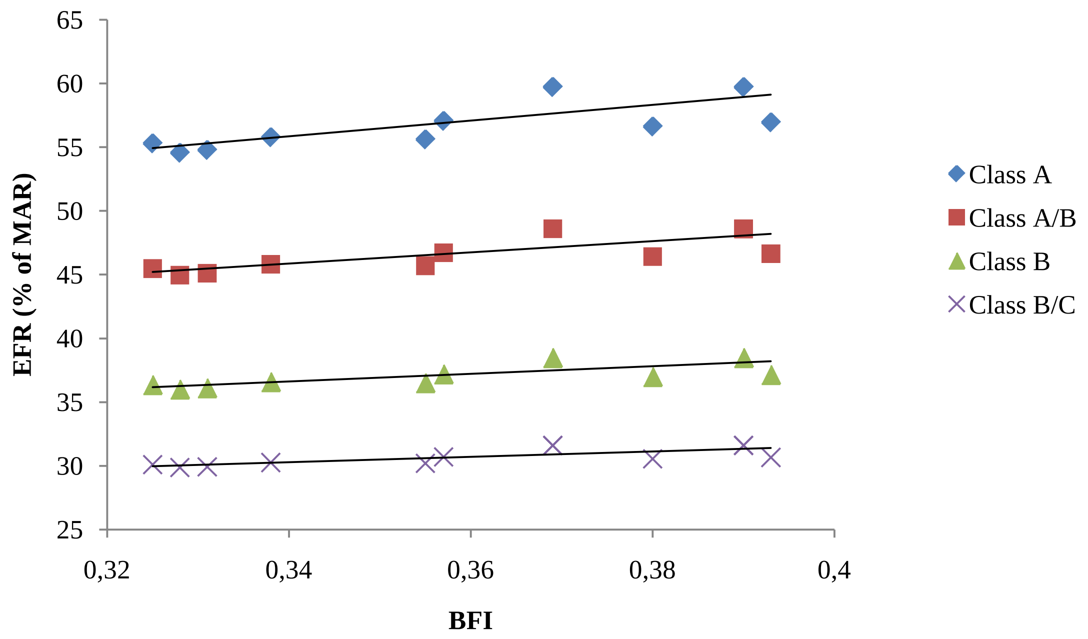


Figure 6.15. Linear regression between EFR and BFI for class A to B/C. The trend lines show a slightly positive correlation with a R^2 value of 0.58.

The EFR for class A varies between 54.5-59.7 of % MAR in the Buzi River basin. The spatial distribution (Figure 6.16) indicates that the higher proportion of MAR is located in the eastern highlands where the % of MAR for EFR-A is between 58.8-59.7 %. The same trend is visible for class A/B where the EFR varies between 45.0-48.6 % of MAR with the highest proportion in the mountain region (Figure 6.17). Figure 6.18 to Figure 6.20 present the results from class B to C. Note that not all the levels of EFR as % of MAR (presented as blue circles) are represented in all the figures, except for the highest (largest circle) and lowest (smallest circle).

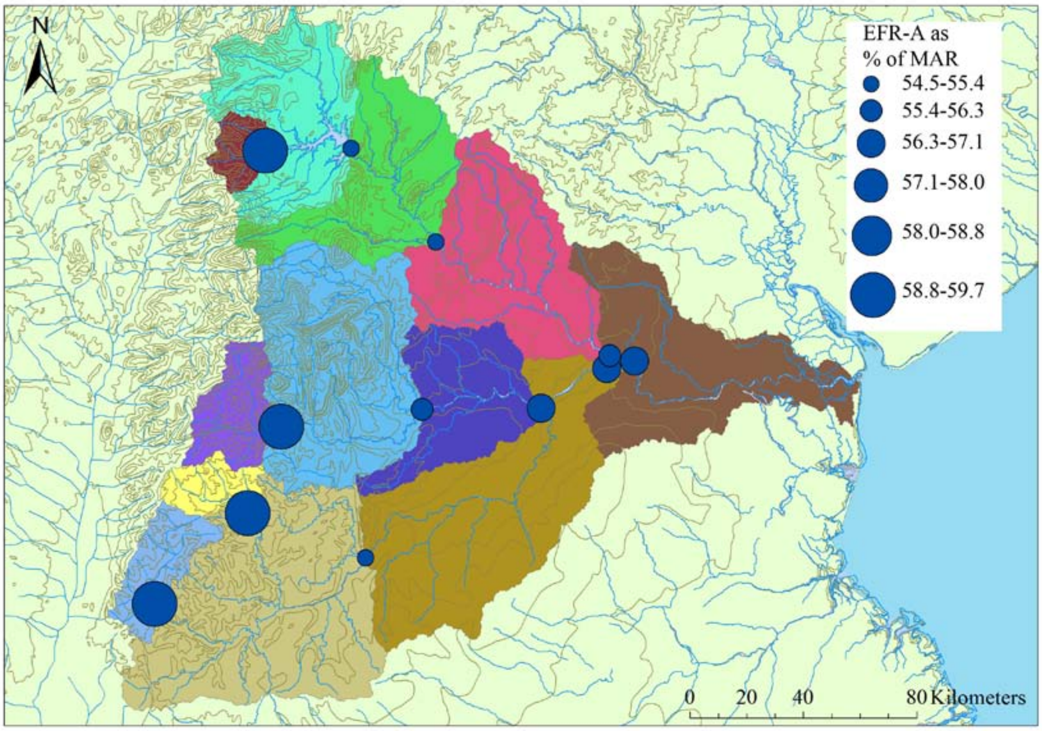


Figure 6.16. Environmental flow requirement expressed as % of MAR required to maintain the ecological state at a natural condition (class A). Average for a class A was 57.1 %.

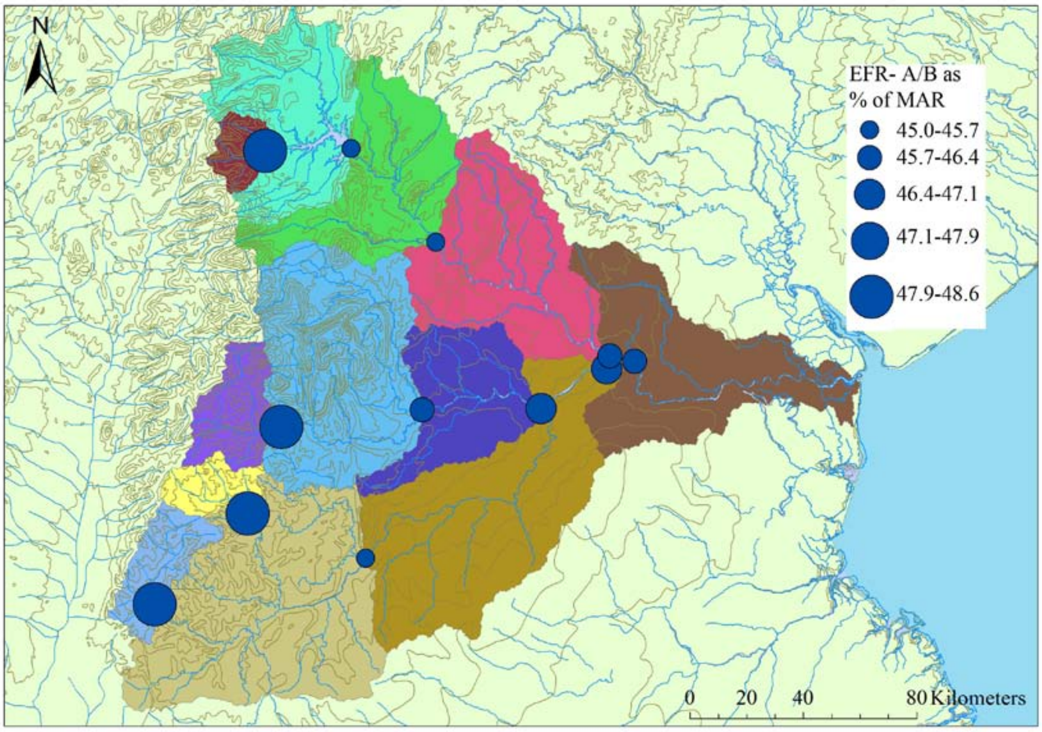


Figure 6.17. Environmental flow requirement expressed as % of MAR to maintain the ecological state at a class A/B. Average for a class A/B was 46.8 %.

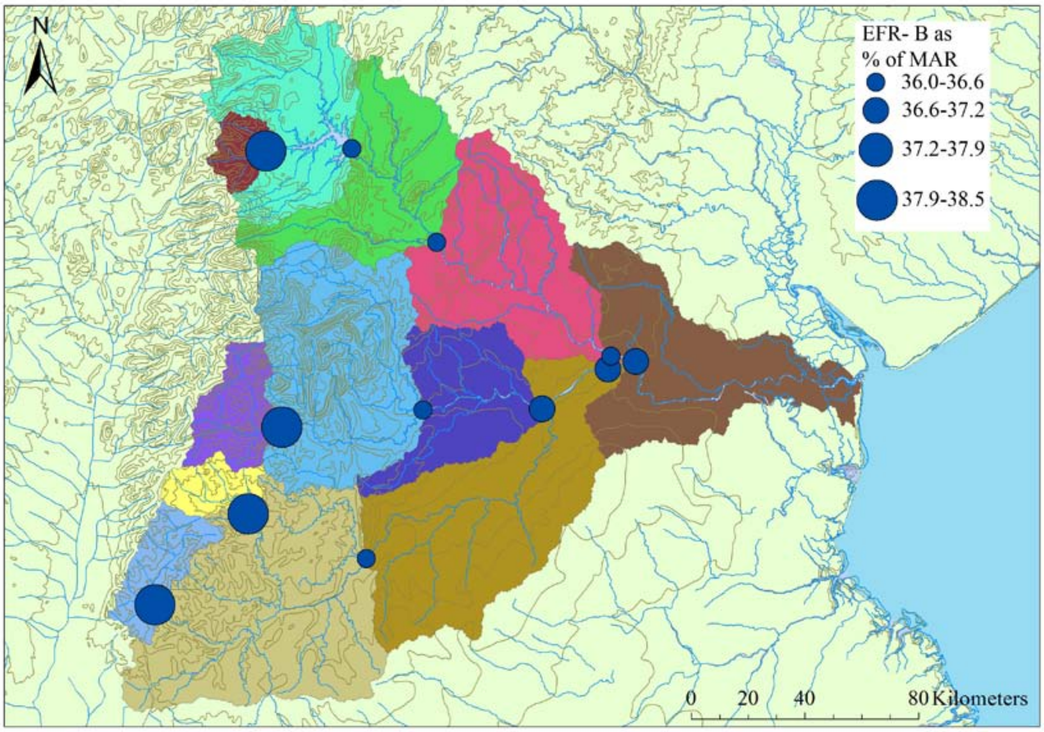


Figure 6.18 Environmental flow requirement expressed as % of MAR to maintain the ecological state largely natural with few modifications (class B). Average for a class B was 37.2 %.

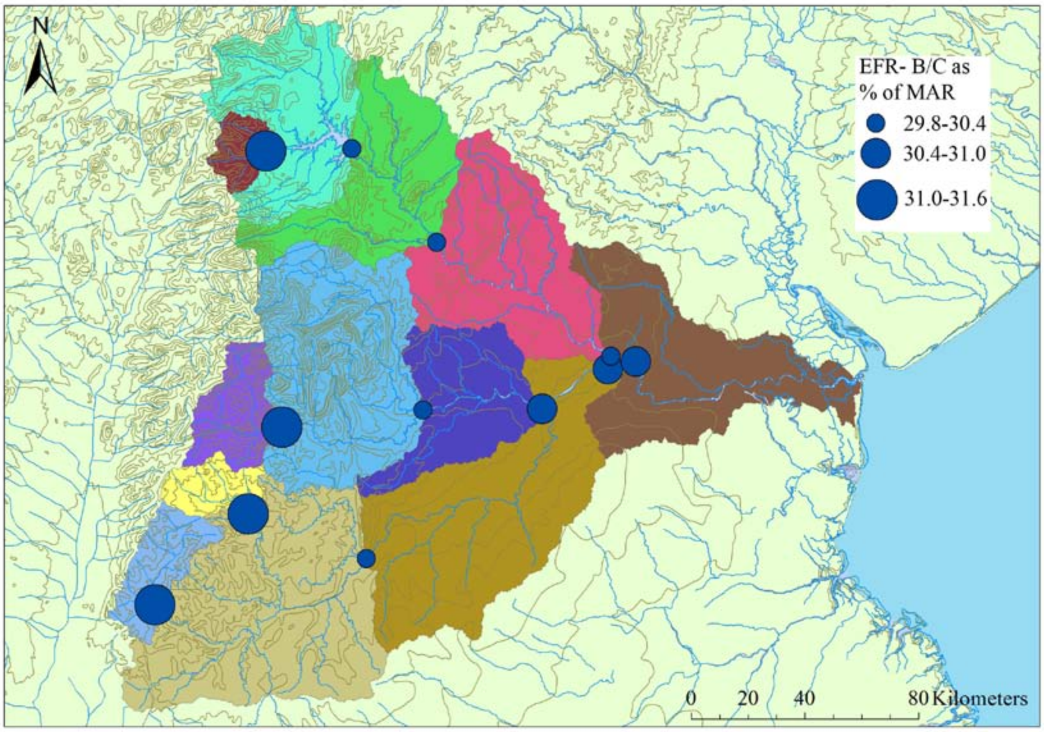


Figure 6.19. Environmental flow requirement expressed as % of MAR to maintain the ecological state at a class B/C. Average for a class B/C was 30.7 %.

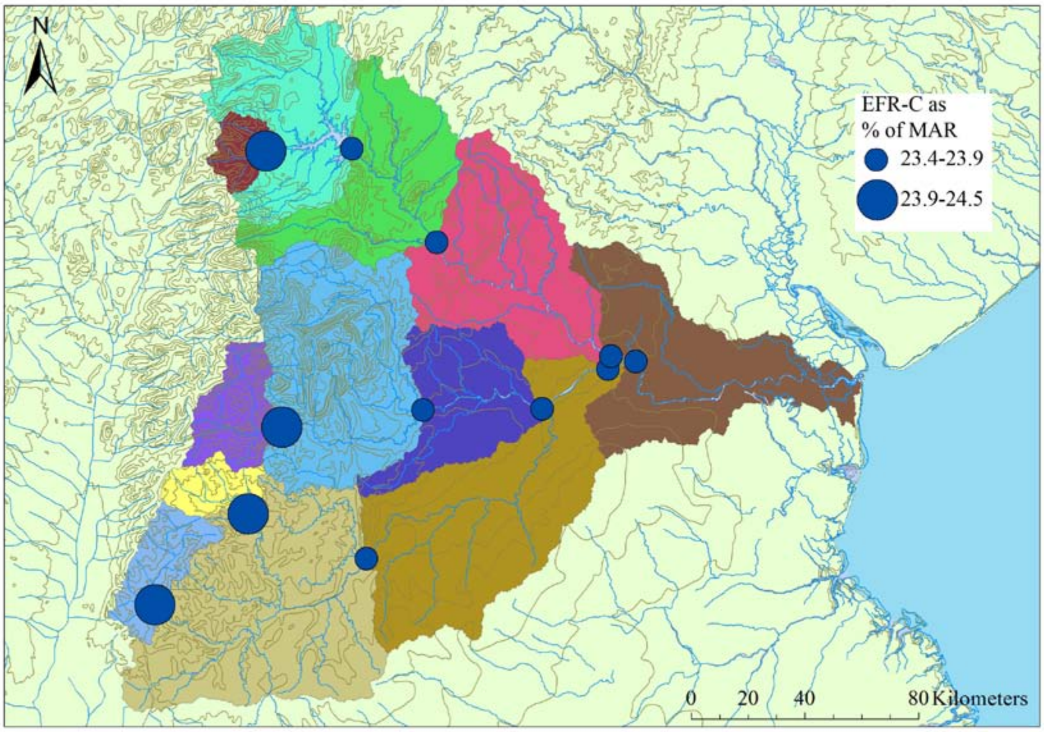


Figure 6.20. Environmental flow requirement expressed as % of MAR to maintain the ecological state at a moderately modified state (class C). Average for a class C was 23.9 %.

Notable is that the distribution between the different EFRs is decreasing from a class A to a class C which can be seen when looking at the legends in the figures. This was also observed when looking into the relationship between EFR and Base Flow Index (BFI) (Figure 6.15). The effect of the hydrological regime seems to be lower the lower ecological class you have.

6.3.2 Effects of ecological class on EFR

The EFR can also be presented as an average monthly value (Figure 6.21). The figure has two lines for each class, the dotted line shows the low flows maintenance and the solid line shows the total maintenance flow. In the magnified graph the total and low flows are the same which means that there is no maintenance high flow during the dry period.

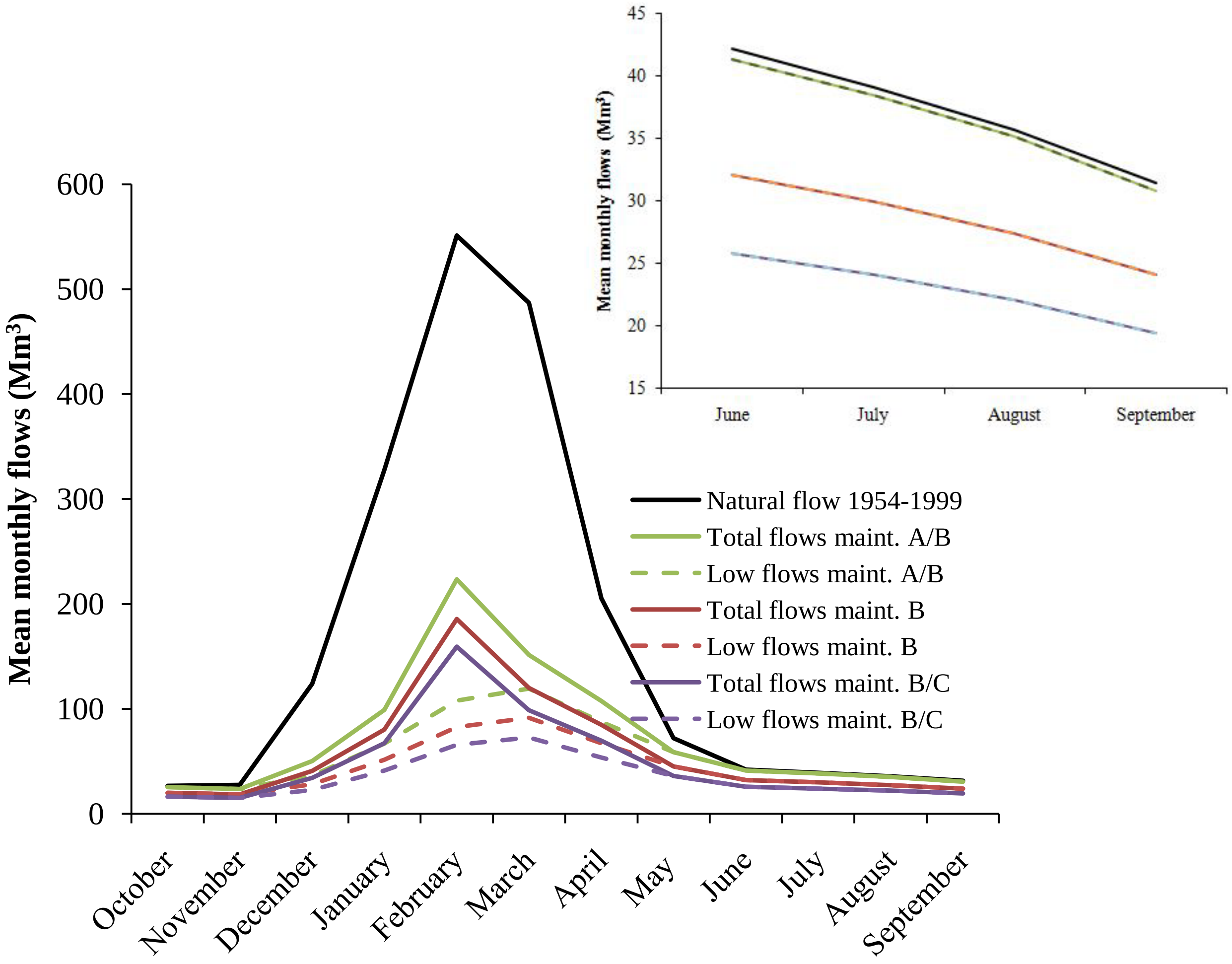
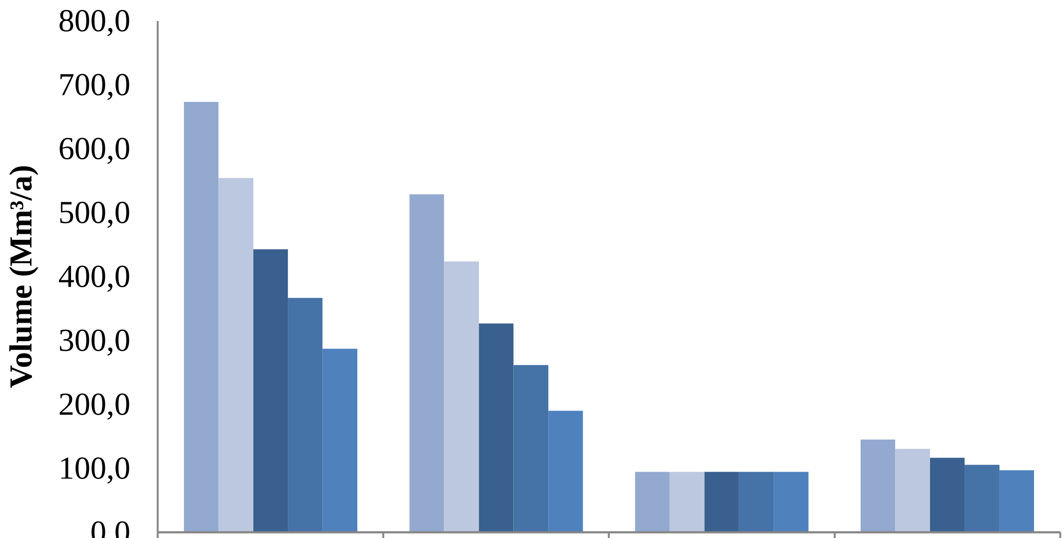


Figure 6.21. Comparison between simulated natural monthly flow volumes in Middle Buzi and monthly maintenance (total and low) flow volumes for class A/B to B/C in Middle Buzi, with month June to September magnified.

The average difference between the requested EFR as % of MAR for a class A and class AB is 10.30 %. For a class AB and B is the difference 9.50 %, between B and BC is the difference 6.48 % and between BC and C is the difference 6.77%.

Another observed difference is that the EFR distribution is larger for a higher class than a lower. For example, the difference between the maximum EFR for a class A and the minimum EFR for a class A is 5.16 percentages points, meanwhile the same difference for a class C is only 1.11 percentages points.

The Desktop Reserve Model also present the environmental flow requirements in volume/year required for the specified class (Figure 6.22).



	Total EFR	Maintenance Low Flows	Drought Low Flows	Maintenance High Flows
A	673,4	528,4	94,1	145,0
A/B	553,9	423,4	94,1	130,5
B	442,7	326,6	94,1	116,2
B/C	366,6	261,4	94,1	105,2
C	286,8	189,8	94,1	96,9

Figure 6.22. The total EFR is the total volume of water released as environmental flow during a one year period. These values are from EFR site Upper Revue. The total EFR decreases when going from a class A to C which means that less water is required for a lower ecological state than for a higher. The drought low flows are the same for all the classes and are equal to the EFR for a Class D, which is not shown in this study.

A flow duration curve (FDC) can be used to analyze how the different flow regime characteristics are affected by the environmental flow requirements. The flow duration curves are based on one specific month (e.g. February) during the time period 1954-1999. In total it gives us 46 months. The flow duration curves include all the extreme years; the wettest and driest. The "normal" monthly flow is found at 50%, which means that this flow is equaled or exceeded at 23 of the months during this time period.

February is the wettest of the months at Middle Revue. The natural flow duration curve for February, at EFR site Middle Revue, (Figure 6.23) shows that the average natural monthly flow in February is 615 Mm^3. The 10% on the x axis shows that approximately 5 months have a flow that is above 1400 Mm^3. The 90% indicates that 90 % of the 46 months (≈41 months) have a flow that is above 30 Mm^3/month. When looking at the duration curves for the EFR flows, the curves for the classes A to C seem very similar. At the 10 % on the line for *Class A Feb* (red line) indicates that the extreme wet months observed on the natural flow (1400 Mm^3/month), would never reach over 550 Mm^3/month when using environmental flows. For a *Class C Feb* is the value even lower, only 315 Mm^3/month. During the years when the flow in February is low is the difference between the natural flow and the environmental flow small.

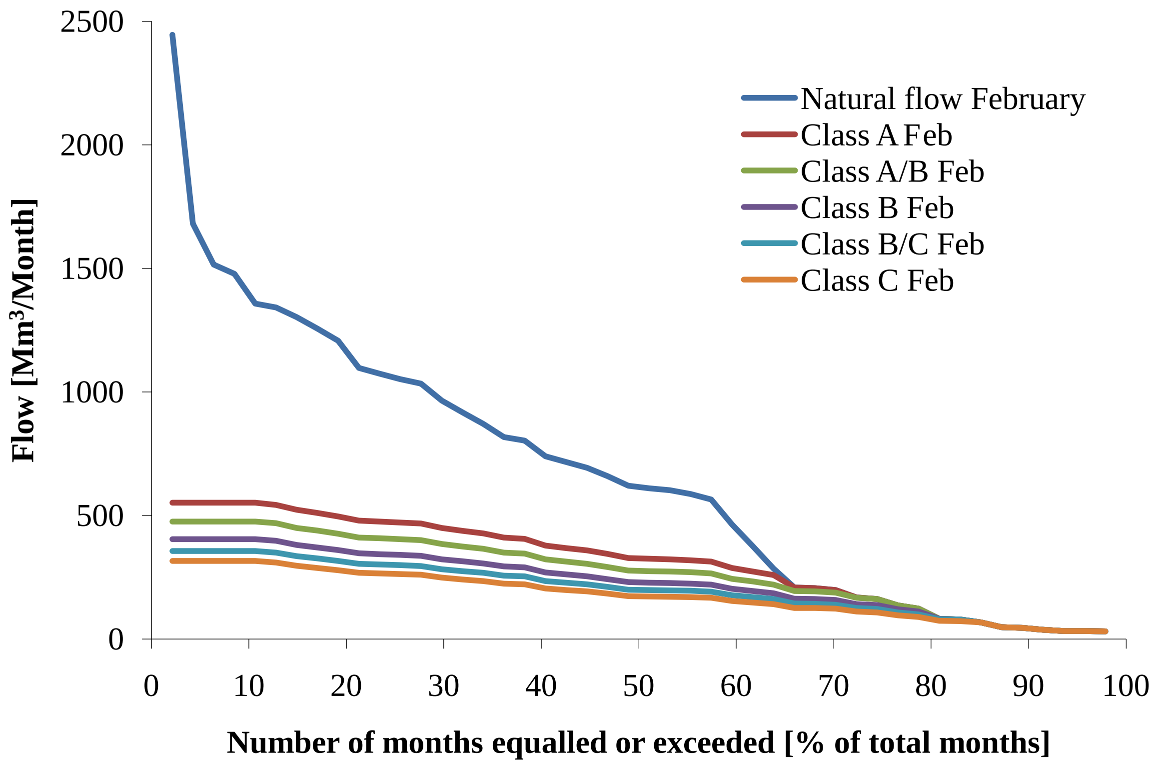


Figure 6.23. Flow duration curve for Middle Revue in February, wet season. The average flow is at 50%.

The monthly flow in Middle Revue is in general the lowest in September from the simulated data used in this case study. The natural average monthly flow (at 50%) is 50 Mm^3/month (Figure 6.24). The EFR flows (*Class A Sep* to *Class C Sep*) show that the EFRs follow the natural flow for approximately 23 of the months. After 50 % (the driest of the September months) the EFR for all the 5 classes drops faster than the natural flow.

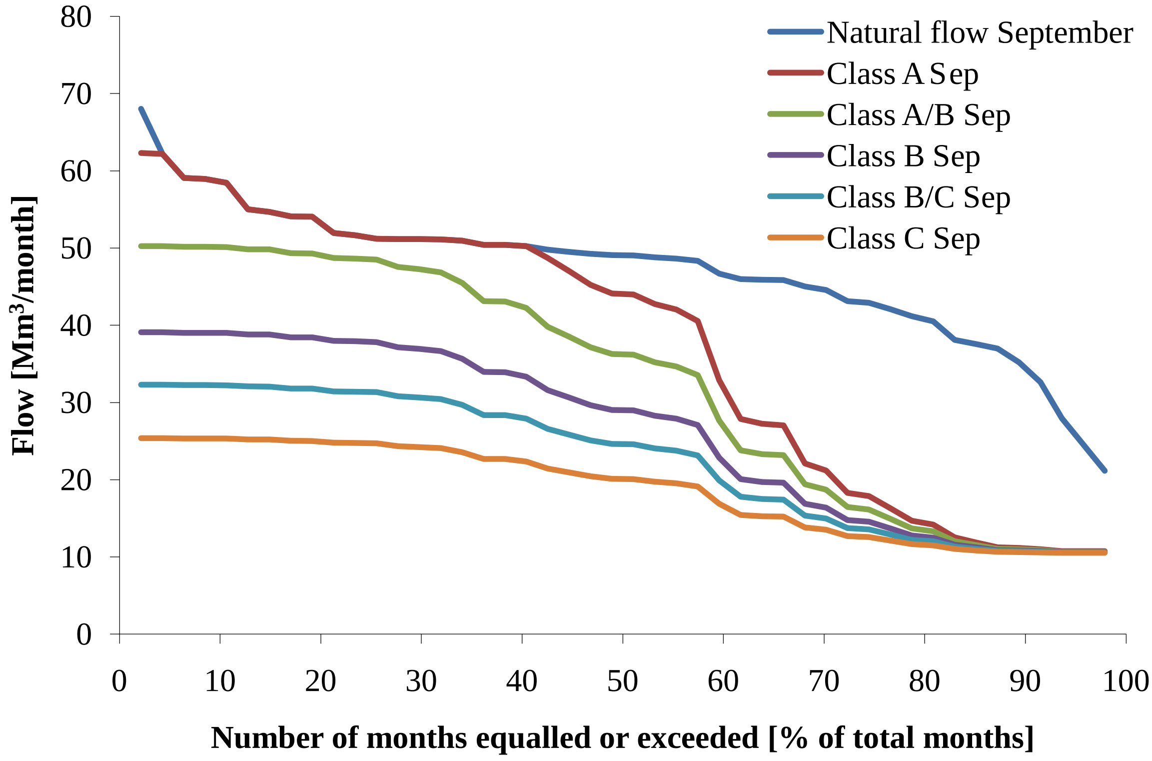


Figure 6.24. Flow duration curve for Lower Revue in September, dry season.

7 DISCUSSION

The underlying assumption in setting environmental flows is that there is some extra water in rivers that can be used by humans. The water left in the river must be enough for the environment to maintain an ecological status defined by humans.

"*Environmental flows describe the quantity, quality and timing of water flows required to sustain freshwater end estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems.*" (Brisbane Declaration, 2007).

The literature study showed that not only the quantity of water is important; the timing and frequency of floods, droughts, low flows and high flows are very important as well (Figure 2.1 and Figure 3.4). The literature study also showed that the advances in environmental flow science have been remarkable while the water policy and management has not been equally successful in implementing environmental flow standards. The environmental flows cannot be seen as an extra resource for e.g. irrigation or water supply for the downstream users. This is one reason why the implementation of environmental flows is difficult and why the water policy and management are highly important.

This discussion will summarize the major findings from this study and give some suggestions for further improvements of setting environmental flow standards in the Buzi River basin.

Characteristics of flow regime
The data used in this study was mean monthly runoff data for the Buzi River for the years 1945-1999. The flow data was generated from rainfall data with the PITMAN model, and once again it should be stressed that the reliability of the flow data was low and that the data was only a draft output from the first modeling session. Extra calibration of parameters could have improved the reliability of the data, but for the level of this study it was assumed that the accuracy level was good enough. The assumption was that these records represent the best available estimate of natural flow conditions and was therefore suitable to use with the Desktop Reserve Model. An improvement would have been to measure the actual flow at the EFR sites at the time of visit. The additional time and costs to do extra measurements does not tie with the aim of this study, which are a first, quick and cheap estimate of the EFR. This would have been useful for validation of the simulated runoff data.

Chicamba Dam with a storage capacity of 2020 Mm^3 and with a natural MAR of 2460 Mm^3/a which represents a dam with a capacity of approximately 80% of MAR. This results in large modifications of the river flow, both by stopping the medium sized floods and regulating flows through releases for power generation. Large floods will however not be stopped by this dam. The impact of this dam on the ecology is large, affecting the seasonality of the flows and stopping the medium sized floods. It is however not possible in this study to determine to what level the river ecology is affected. It would however be interesting to compare the environmental flows calculated with the Desktop Model with the observed flow at the site below the dam to see if the current operation of the dam is complying with the calculated environmental flow.

Selecting EFR sites and setting the present ecological status
The methodology for deciding the present ecological status was selected mainly because of its simplicity and also because it was previously tested and used in other parts of southern Africa.

The methodology was developed by Kleynhans, who today is one of the major scientists in the field of Eco Classification. Kleynhans and Louw (2007) have developed a model called EcoQuat used for Desktop EcoStatus level 1. This EcoQuat model uses the Habitat Integrity as a tool for analyzing the drivers and responses for rating of fish, invertebrates and vegetation. Fish and invertebrate rating was not included in this study due to time and resource limits. The vegetation rating was partly included in the habitat integrity assessment. The level of uncertainty is therefore high for the assessment of the present ecological status. In a full scale environmental flow assessment the present ecological status is only a part of the Eco Classification process. It is always better if the importance and sensitivity of the river are assessed together with the full EcoStatus for deciding on a Recommended Ecological Category. An improvement for studies that call themselves Desktop studies would be to follow the EcoQuat model throughout. Unfortunately, the results of any ecological study, even by expert Ecologists, depend on historical knowledge of the biota and drivers of the river. Even an in-depth study will not surely produce high confidence results as a once-off visit to a river could be very misleading. Many factors such as wet or dry cycles and seasonal differences could influence the results.

If the study was to be performed at a more detailed level it would be a good idea to use expert knowledge from different sectors for assessing the ecological state of the river's characteristics. The experts need good knowledge of the area to be able to analyze for instance differences in the river ecology. The present ecological status is built on comparison with the natural pristine conditions. However this information may in many areas, especially in the developing regions of the world, be very difficult and time consuming to find, and in many instances non-existent. To find long term flow data, rainfall measurements or land use data can also be difficult.

In this particular study, the simulated MAR data used for modeling the environmental flow requirements was very rough. When implementing the EFR the simulated MAR data is no longer important as the new EFR is calculated from observed daily/monthly measurements of the flow. The only problem with using the "wrong" hydrology is that you have another index as input to the Desktop Reserve Model. This case study showed that the differences within the Buzi River basin for a class were quite small, around 3-4 % of MAR. If we assume that the simulated hydrology in average was 20% wrong this would perhaps affect the EFR in the magnitude of 1-2% up or down. However, the case study also showed that going up or down one ecological class results in a 6-10% difference in the EFR. This could be as much as 120 Mm^3/year (Figure 6.22). By that an error in the historic hydrology has a very limited effect compared to an error in setting the ecological class.

In this study the present ecological state at the EFR site below Chicamba Dam was classified as a Class C, and at all the other sites it was found to be in a Class B. These are quite realistic results, and compares well with the results from Pungwe River basin (north of Buzi River basin). The ecological status along the Buzi River would probably be higher, around A/B and even A for some of the remote sites. I did however not include any ecological states for these sub-basins in the result section because of the low confidence in not being able to visit the sites and therefore not completing the Eco Classification questionnaire.

The number of sites used in this study was probably too many. According to Estelle Van Niekerk (pers. comm.) it is enough and ideal to have a site for each homogeneous ecological river stretch. This could for instance be downstream of a dam, in the mountain region, from a plateau to a flat area or at a possible contamination point. Since it is well-known that there is very little development in the Buzi River catchment it would probably have been enough for this level of study to only select sites at the Upper Revue (below the dam), Middle Revue (elevation change), Zonue Zimbabwe (point of possible contamination) and Upper Buzi (likely a pristine site).

The Buzi River flows into the Pungwe Estuary close to the town Buzi. Estuaries are dependent of sediments that get flushed out during floods and high flow periods. To calculate the environmental flow requirements for the estuary requires knowledge about the flow from Pungwe River as the two flows will interact. The environmental flow for the estuary was not included in this study but a rough suggestion is that the releases from Chicamba Dam should be more similar to the natural condition of high flows. Furthermore should any new dam built in Buzi River basin be constructed to maintain the flow characteristics of the river, and include sediment bypasses and sluice gates to allow for sediment transportation (Krchnak *et al*., 2009).

The present ecological state

The mining in the Buzi headwaters is affecting a large part of the river basin. The use of mercury for flocculating gold composes a health risk for the people in direct contact with it. According to Mr. Manuel Américo Fobra (pers. comm.) the level of mercury in Chicamba Dam was at present very low, below measurability. Mr. Fobra said that full scale investigations had been done to analyze the mercury problem and that they had not found any traces of mercury during their studies. Bank erosion caused by mining is also a huge problem. The activity on the banks causes erosion which in turn leads to increased amount of sediments. To stop, or forbid, the mining is not realistic at present time, but a suggestion could be that the mining is forbidden, or at least reduced, during periods of low flows. When the water flow is low the sediment concentration will be high and the impact on the environment and water quality will be high.

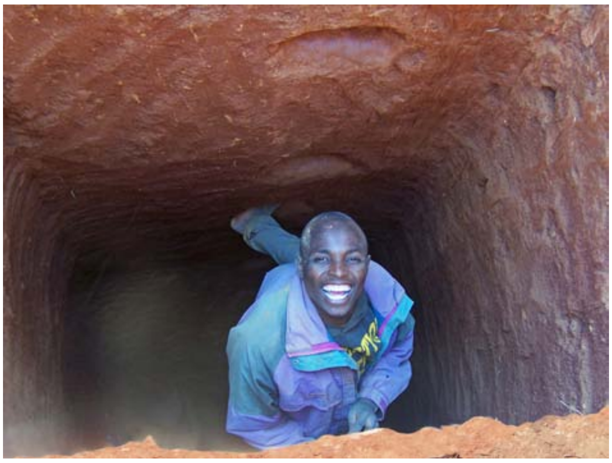


Figure 7.2: Gold is found approximately 10 meter down into the soil and deep handmade holes are used for getting down (Photo Lovisa Lagerblad) .

Figure 7.3: Large-scale irrigation is not yet any problem in the Buzi River basin. This water is however used for irrigating sugar canes along the Buzi River (Photo Lovisa Lagerblad).

The observed bank and erosion problems in the Revue River might also have been caused by natural vegetation removal. During the field study the vegetation at the observed sites along the river seemed to be natural. However, the number of sites visited at the field study were limited. Meanwhile, satellite images from Google Earth shows that the deforestation around the Revue River is fairly widespread. This also comports with what Mr. Manuel Américo Fobra General Director at ARA-Centro (pers. comment) believed was one of the biggest environmental problems in the region. According to him the deforestation is due to uncontrolled agriculture where trees are cut down to produce coal for selling. Trees that are cut from the slopes are of extra importance because they stabilize the mountain soils. Another possible reason for the deforestation is burning. According to Mr. Adelino Mugadui (pers. comm.) people burn trees to make hunting easier. The erosion is also, said Mr. Adelino Mugadui, except from mining, an affect of inadequate farming practices where wrong techniques are used.

Bank erosion due to decreased bank stability will cause sedimentation and eventually possible collapse of the river bank resulting in a loss or modification of both instream and riparian habitats. The increased sedimentation that was observed to some extent at all visited sites can have several negative impacts. It can decrease the amount of available sunlight in the water through increased turbidity, damage fish by irritating and scouring their gills, reduce the success of visual predators, and fill up channels and reservoirs, to name but few effects. The reduced water quality from the increased levels of sediment can also cause problems with irrigation. Bruce Meikle (pers. comm.) at Mafambisse Sugarcane estate (uses water from Pungwe River) said they could not use drip irrigation because salt and metals from the sediments clogs up the drip-holes. They are therefore forced to use sprinkler irrigation which is less effective and more water consumptive.

Figure 7.3 Chicamba Dam is an impoundment (man-made artificial lake) that when situated in headwater areas can affect the flow regime of the entire river (Renöfält *et al*., 2009). (Photo Lovisa Lagerblad)

Figure 7.4 Line ferry for crossing the Buzi River close to the town Buzi (Photo Lovisa Lagerblad).

Hydropower fundamentally transforms rivers and their ecosystems (Renöfält *et al*., 2009) but predicting the effect from Chicamba Dam on the ecosystem was not easy. Changing the seasonal flow variables can reduce habitat availability. It can also affect moving of sediments, water temperature, reduce high flow, prevent fish from migrate upstream to spawn etc. The effects from the dam in this study were rated to the level that a small loss and change in natural habitats may have taken place. The uncertainty in this approximation is high and it is solely based on assumptions and observations, with no biological or other surveys to confirm this. In the Zambezi River the Cahora Bassa Dam has reduced high flows which could be the reason to large reductions in fish and shrimp catches (Box 4). Apart from the environmental impact this is also an economical loss for local fishermen.

One of the questions this thesis aimed to answer was to determine if it is possible to set the present ecological state of a river with a limited amount of data. This study showed that it could be possible but that the confidence level will be low. Further, to evaluate the result is difficult as there is no "right solution" to compare with. Furthermore there is not enough information available to get an indication of how good or bad the estimate is. A good way of improving the process of setting the ecological state could be to develop a "user-friendly guide for setting ecological status" with simple and easy hand-on steps to follow. The manual should be constructed in such a way that the involvement and knowledge of stakeholders play a central role.

A group of scientists (Poff *et al*., 2010) has recently presented a new framework for developing regional environmental flow standards. The framework *the ecological limits of hydrologic alteration* (ELOHA) is thought to work as a platform for assessing environmental flow requirements for many streams and rivers simultaneously. This includes those for which little hydrologic or ecological information exists. In the ELOHA framework, river classification focuses primarily on the hydrologic regime as the main ecological driver. Rivers will be classified according to ecologically meaningful streamflow characteristics, and similar rivers can be identified. This will be used to support the development of relationships between flow alteration and ecological degradation/characteristics. However, the scientists recognize that the strength of the relationship between flow alteration and ecological response is probably interpreted in various ways (Poff *et al*., 2010). However, this approach means that some detailed studies are required to be able to compare the results of the detailed studies with the results of the studies where little information is available.

Environmental flow requirements
The environmental flow requirement expressed as % of MAR to maintain the different classes (A to C) seems quite realistic compared to other similar studies in South Africa and Zimbabwe. For a class A the average required amount in Buzi River was 57.1 % of MAR. A study from Zimbabwe shows that the environmental flow requirement from the eastern highlands (sub-basins Zonue Zim, Rusitu Zim and Mossurize Zim) is between 51-67 % of MAR for a Class A (Mazvimavi *et al.,* 2007). For a Class B this study showed that the EFR requires an average of 37.2% of natural MAR compared to the Zimbabwean estimate of between 31-42 %. For a class C the average of Buzi River was 23.9% while the Zimbabwean study had an estimate of 16-25% (Mazvimavi *et al.*, 2007). Both studies used the Desktop Reserve Model by Hughes and Hannart (2003).

An environmental flow study done with the Desktop Reserve Model for the Great Ruaha River catchment in Tanzania shows that to maintain the basic ecological functioning of the Great Ruaha River requires an average water allocation of 635.3 Mm^3/a, equivalent to 21.6% of mean annual runoff (MAR). In that study the recommended ecological status was set to C/D, which is lower than the PES but reflects the importance of allowing water abstraction for local communities (Kashaigili *et al.*, 2007). This study from the Buzi River basin showed that to maintain a class C requires approximately 24 % of MAR.

Compared to the findings from Tennant (1976) which are based on hydrological methods to evaluate the EFR, he suggests that 60% of the MAR provides excellent habitats, which is close to the result for class A calculated with the Desktop model used in this study. According to Tennant for good survival conditions of most aquatic forms an allocation of 30% is required, which corresponds to a class B/C environmental flow. It should be remembered that the Desktop model is a regional model and sensitive to various indexes to calculate the EFR, while the Tennant results seems to be more generalised.

Another question this study aimed to answer was how much the present ecological state affected the environmental flow requirements. This study showed that when using the Desktop Reserve Model the average difference between the requested EFR expressed as % MAR was 10.30 % between classes A and A/B, 9.50% between classes AB and B, 6.48% for classes B and B/C and 6.77% between BC and C. This could be interpreted as the sensitivity between the higher classes is larger than between the lower classes. The study also showed that the range within a class was higher for a class A than for a class C.

Sub-basins with BFI values less than 0.20 will typically have no flows during the dry season, while sub-basins with high BFI 0.5-0.7 typically have perennial rivers (Mazvimavi *et al.*, 2007). This study showed that the average BFI for Buzi River basin was 0.37. The Buzi rivers have been assumed to be perennial, but the study shows that during the dry season, flows for some parts of the basin are very low. Rivers with BFI close to 1 are less variable than those with lower BFI values (Kashaigili *et al.*, 2007), and the rivers in Buzi River basin are variable in flow, so a BFI at 0.37 was probably realistic.

Flow duration curves

The flow duration curve (FDC) of EFR compared to the natural FDC for the wet season (Figure 6.23) shows that required flow for February are between 80-100% equal for all of the classes, including the natural flow. This could be interpreted as that during low flow years, or years with drought, all the water in the river must be reserved for the environment. The FDC also shows that the environmental flow was very low during periods of floods and high flow for all the classes. Looking at the driest month September (Figure 6.24) the natural flow was the same as the flow of class A between 5-43% of the time. This means that if the class A was to be applied in reality during 38% of the time none of the water in the river could be used for water abstraction. During periods of drought the environmental flow was very low compared to the natural flow.

These results are not realistic from an ecological or water management point of view. According to Denis Hughes (pers. comm.) the default regional parameters that have been used in this study have not been thoroughly tested for this area. He further says that some of the parameters would require modification on the basis of some expert opinion. The diagrams shows that the maintenance flows are too high in the dry season and too low in the wet season. The maintenance distribution factor could, according to Hughes, be much higher as this would increase wet season flows and decrease dry season flows. For the dry season the opposite is true; the results showed that the model asked for too much water during high flows and too little water during low flows, leaving not room for development.

The maintenance distribution factor was not modified during the calculation of environmental flow in this study because the purpose of this study was to determine the usefulness of a high level study. An improvement to the EFR will be to calibrate the model for the Buzi River basin and adjust the maintenance distribution factor manually according to expert opinion.

Implementing environmental flows

South Africa was the first country in the world to legislate the concept of “ecological reserve” as a right of law. However, none of the calculated environmental flows has been implemented yet. Richter (2009) says that one problem with implementing environmental flows is that the management of water resources is uncoordinated with many different jurisdictions for the regulation of surface water, groundwater and dams. This problem is extra complicated for transboundary rivers. The water sector in Mozambique has a legal framework consisting of five major parts. Another obstacle with implementing environmental flows is that there are uncertainties in the prediction of weather events and climate change and therefore in how the water availability will be during the coming weeks, months or years. To set fix volumes of how much water that should be left in the river every month is unfortunately not working when the intra-annual variation is high, like in the Buzi River basin and a solution to implement the EFR is required.

8 CONCLUSIONS

- The Desktop Reserve Model can be used for rapid estimations (with low confidence) of environmental flow requirements in the Buzi River basin. This indicates that similar river basins in southern Africa perhaps could use this method for sustainable river management. However, some parameters require modification because they have not been thoroughly tested for this area. Before the result could be used with any confidence it should be confirmed by a more detailed investigation such as the BBM.

- To maintain the ecological state in Buzi River basin largely natural (ecological class A) an average allocation of 57 % of mean annual runoff (MAR) is required. The present ecological state was determined in Revue River to B and C. To maintain the Revue River at its present ecological state requires an environmental flow between 23-37 % of MAR. Further studies are recommended to improve or determine the validity of these results.

- The Desktop Reserve Model is sensitive to the ecological class. The difference between two classes on the EFR expressed as % of MAR, is in the magnitude of 5-10 % of MAR. The effect on the EFR from errors in the hydrology used for calculating the EFR is probably less important than the consequences of selecting the wrong ecological class.

- The major environmental threat in Revue River observed in this study was erosion, increased sediment levels and flow modification through abstraction for irrigation and hydropower dams. The erosion is a consequence from gold mining, inadequate farming practices with wrong techniques and deforestation.

- To determine the present ecological state in data sparse regions is possible, but the confidence level of the results will be low. The relationships between ecological changes and flow alterations must be investigated in detail for the region before the ecological status can be decided and the right EFR used. However, the interaction between hydrology and ecology is very complex and continuous monitoring will be required.

- The flow regime of a river is important; the timing and frequency of floods, droughts, low flows and high flows plays a central role in assessing the environmental flows. The advances in environmental flow science have been remarkable but the water policy and management has not been equally successful in implementing environmental flow standards.

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APPENDIX A

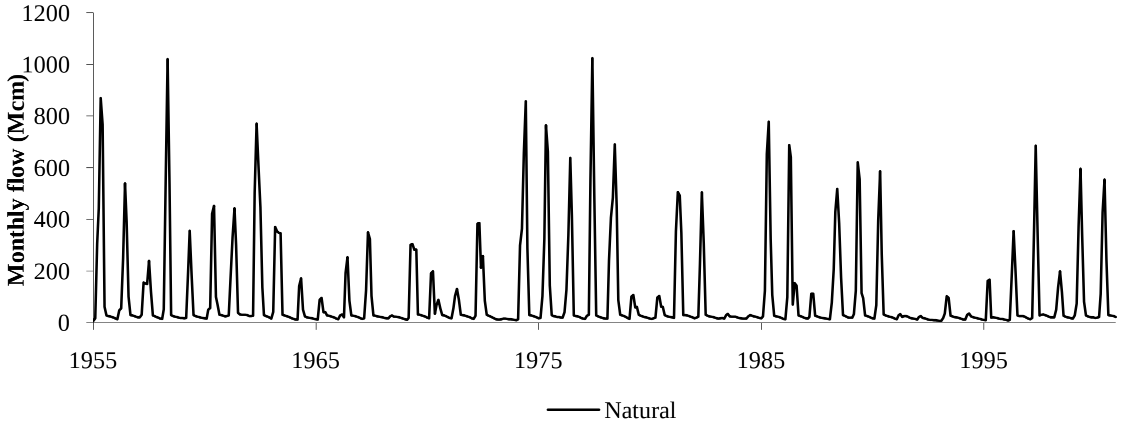

Figure A1. Natural monthly flow in Upper Revue. The maximum flow recorded for this time period was in February 1958 with a monthly flow of 1020 Mcm. Several periods of droughts have been experienced, e.g. between 1991-1995.

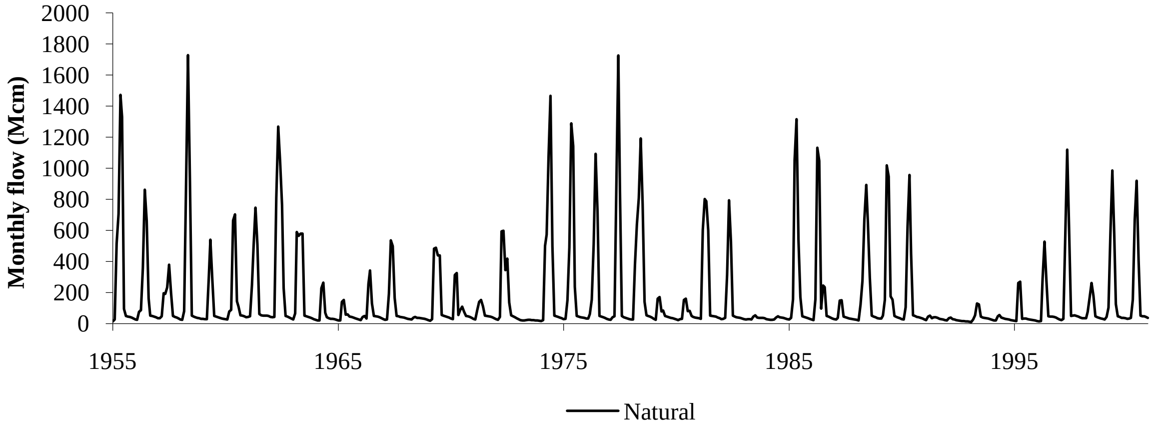

Figure A2. Natural monthly flow in Middle Revue. Maximum monthly flow was recorded in February 1958, same time as for Upper Revue.

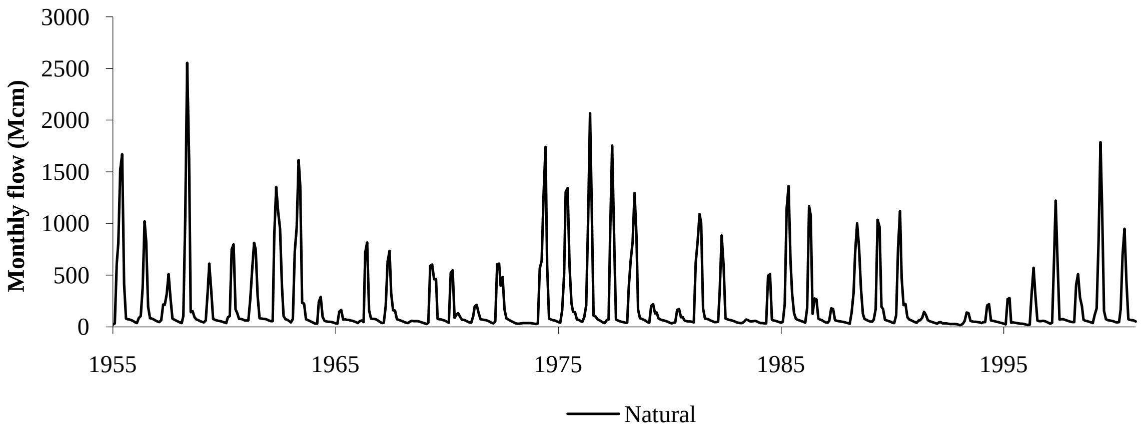

Figure A3. Natural monthly flow in Lower Revue.

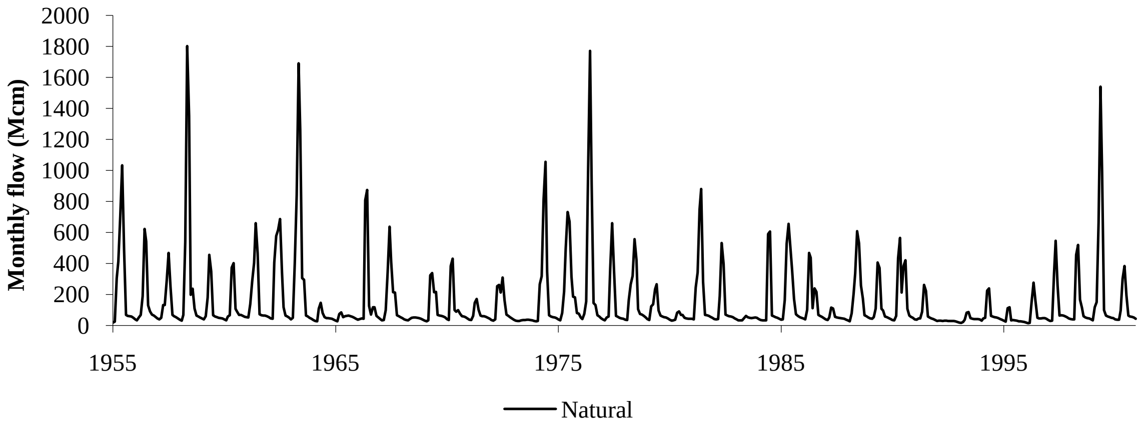

Figure A4. Natural monthly flows in Upper Buzi. Maximum monthly flow was recorded in February 1958, same time as for Upper and Middle Revue.

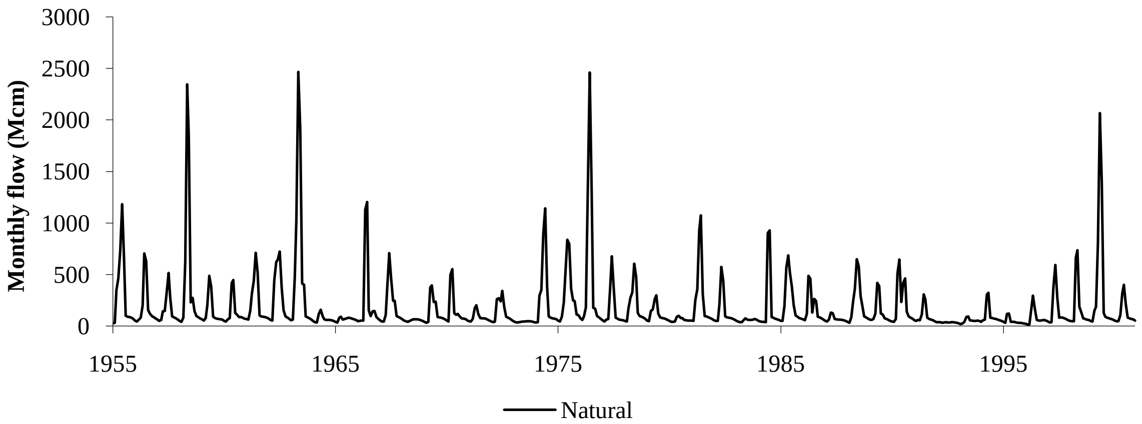

Figure A5. Natural monthly flow in Middle Buzi.

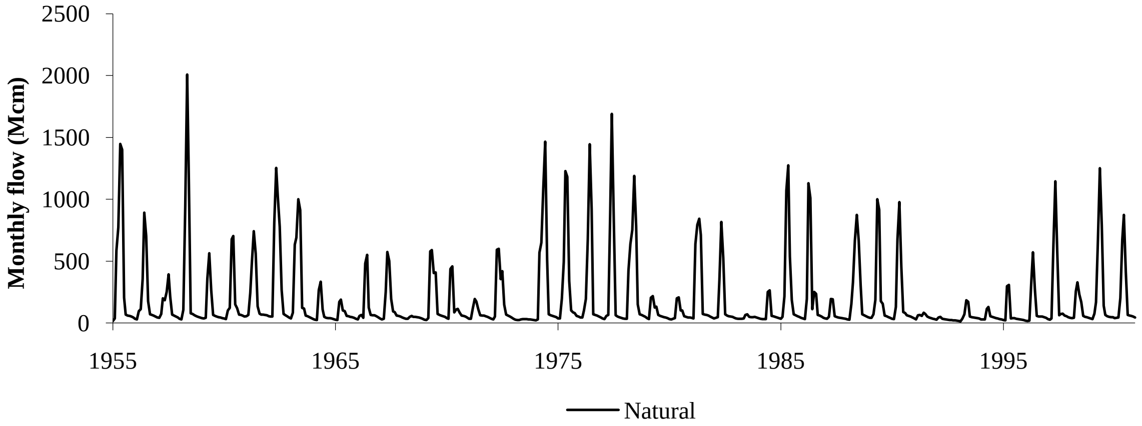

Figure A6. Natural monthly flow variation from Lower Lucite in the central part of the river basin.

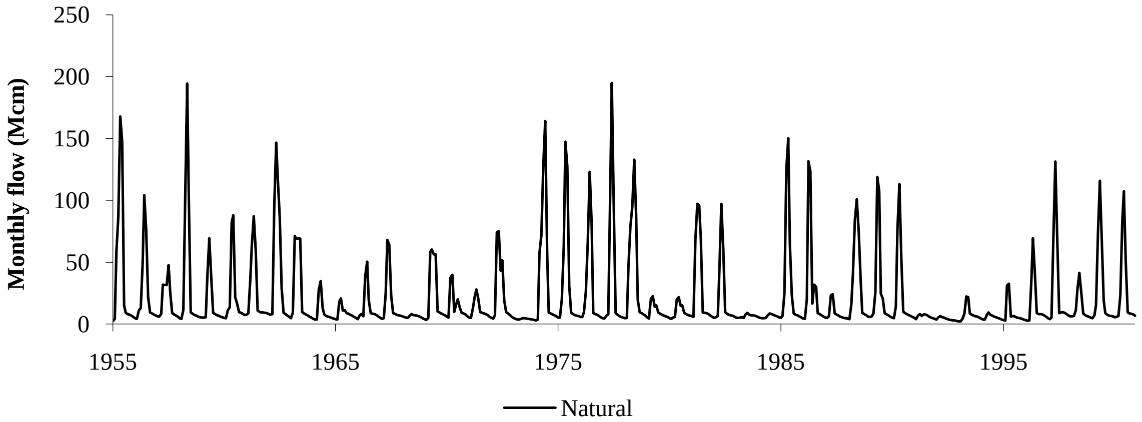

Figure A7. Natural monthly flow variation from sub-basin Buzi-Zimbabwe.

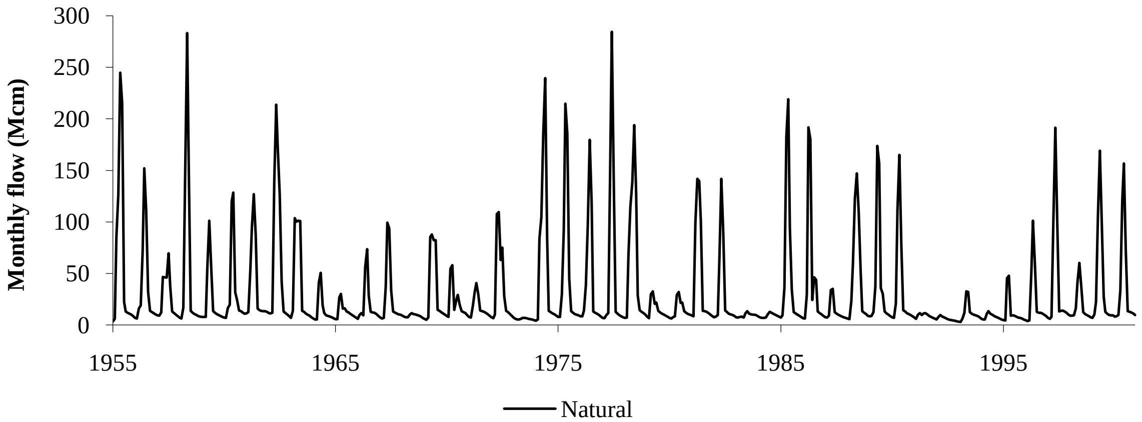

Figure A8. Natural monthly flow variation from sub-basin Mossurize- Zimbabwe.

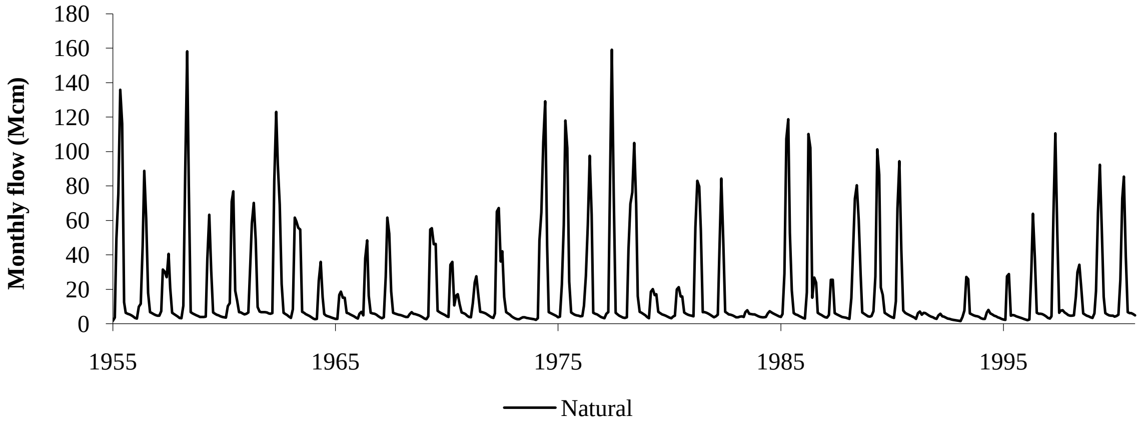

Figure A9. Natural monthly flow variation from sub-basin Zonue-Zimbabwe.

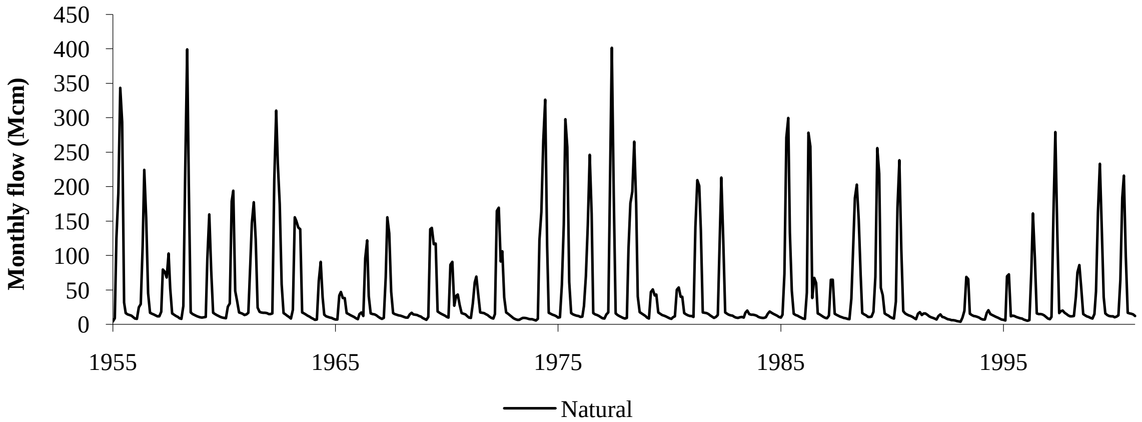

Figure A10. Natural monthly flow variation from sub-basin Rusitu-Zimbabwe.

APPENDIX B

Table B12. Spreadsheet from Kleynhans (1996) with results from setting the present ecological state in five sub-basins of Buzi River basin

INSTREAM HABITAT INTEGRITY EVALUATION					
Delineation:	**Upper Revue**	**Middle Revue**	**Lower Revue**	**Lower Buzi**	**Middle Buzi**
PRIMARY					
Water Abstraction	4.0	3.0	3.0	4.0	3.0
Flow Modification	10.0	8.0	5.0	5.0	0.0
Bed Modification	13.0	10.0	7.0	6.0	10.0
Channel Modification	1.0	1.0	2.0	3.0	3.0
Water Quality	6.0	5.0	4.0	5.0	6.0
Inundation	0.0	0.0	4.0	0.0	0.0
TOTAL (OUT OF 150)	34.0	27.0	25.0	23.0	22.0
SECONDARY					
Exotic Macrophytes	0	0	0	0	0
Exotic Fauna	0	0	0	0	0
Solid Waste Disposal	0	0	0	0	0
TOTAL (OUT OF 75)	0	0	0	0	0
INSTREAM HABITAT INTEGRITY SCORE	77.8	85.6	84.9	87.6	88.1
INTEGRITY CLASS	**C**	**B**	**B**	**B**	**B**

RIPARIAN HABITAT INTEGRITY EVALUATION					
Delineation:	**Upper Revue**	**Middle Revue**	**Lower Revue**	**Lower Buzi**	**Middle Buzi**
Vegetation Decrease	2.0	5.0	5.0	5.0	5.0
Exotic Vegetation	0.0	0.0	2.0	1.0	1.0
Bank Erosion	10.0	10.0	10.0	6.0	10.0
Channel Modification	3.0	3.0	3.0	3.0	1.0
Water Abstraction	5.0	1.0	3.0	4.0	3.0
Inundation	0.0	0.0	4.0	0.0	0.0
Flow Modification	11.0	8.0	6.0	4.0	2.0
Water Quality	5.0	4.0	3.0	5.0	7.0
TOTAL (OUT OF 200)	36.0	31.0	36.0	28.0	29.0
RIPARIAN ZONE HABITAT INTEGRITY SCORE	73.9	83.9	81.6	85.5	84.7
INTEGRITY CLASS	**C**	**B**	**B**	**B**	**B**
RIPARIAN VEGETATION INTEGRITY SCORE	96.0	90.0	86.0	88.0	88.0
RIPARIAN VEGETATION INTEGRITY CLASS	**A**	**A**	**B**	**B**	**B**

OVERALL RIVER HEALTH					
Delineation:	**Upper Revue**	**Middle Revue**	**Lower Revue**	**Lower Buzi**	**Middle Buzi**
Instream					
Instream Habitat Integrity	77.8	85.6	87.1	87.6	88.1
Riparian					
Riparian Vegetation Integrity (Derived from rip zone integrity)	96.0	90.0	86.0	88.0	88.0
Riparian Zone Integrity	73.9	83.9	81.6	85.5	84.7
RIVER ECOSTATUS/INTEGRITY/HEALTH	75.8	84.8	84.4	86.5	86.4
PRESENT ECOLOGICAL STATE (PES)	**C**	**B**	**B**	**B**	**B**

APPENDIX C

Table C1. Exact location of the EFR Sites.

EFR Site	Name	Location	
		S	E
1	Zonue Zim	19°10'13,982"	32°52'48,062"
2	Upper Revue	19°09'22.73"	33°08'42.59"
3	Middle Revue	19°27'30,468"	33°25'33,622"
4	Lower Revue	19°45'55,34"	33°50'45,29"
5	Lower Buzi	19°49'14,998"	34°1'6,026"
6	Middle Buzi	19°55'56,56"	33°49'35,31"
7	Lower Lucite	19°58'1,827"	33°46'40,521"
8	Upper Lucite	19°59'17,088"	33°22'38,012"
9	Rusitu Zim	20°2'25,241"	32°58'10,416"
10	Buzi Zim	20°19'58,9"	32°50'13,76"
11	Upper Buzi	20°28'8,098"	33°10'55,573"
12	Mossurize Zim	20°36'4,753"	32°30'34,668"

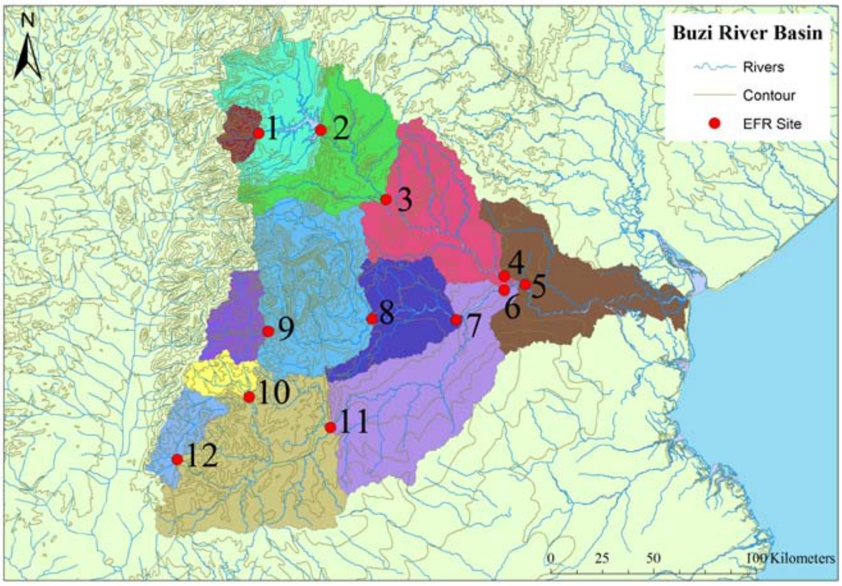

Figure C1. The Buzi River basin with its twelve sub-basins. The red dots are the EFR sites used in this study.