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Implementing environmental water requirements in Buzi River basin, Mozambique

An impact analysis based on the Water Resource Yield Model

Stéphanie Nicolin

ABSTRACT

Implementing environmental water requirements in Buzi River basin, Mozambique
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In areas where clean water is a scarce resource, balanced water consumption is necessary. This can be achieved by assigning each water consumer a proportionate share of water, in relation to what is available the system. Balanced water consumption should also include reserving water for the ecosystems, with the intention to maintain a good ecological status in the area. This latter reservation, essential for the river and its ecosystems, is called *Environmental water requirements* or *Environmental flows*.

The objective of this thesis was to study the water consumers and the impact of implementing environmental water requirements in a specific river basin. The area that has been studied is the Buzi River basin, in Mozambique. A field study was carried out in the area, in order to collect water consumption and technical data for the study.

The analysis of this thesis is based on the South African "Water Resource Yield Model" (WRYM), developed for system analysis of water resources. The model is based on a water penalty system, where each consumer is assigned a priority in order to balance the water consumption within the limits of availability.

The results show that the introduction of environmental water requirements would reduce the amounts of available water for consumptive use by approximately 30% in order to maintain the present ecological status of the area. Furthermore, the study demonstrates a significant trade off between the level of generated hydropower and the amount available water for consumptive use in the system. However, it can *not* be concluded from the results that environmental water requirements would reduce the production of hydropower in the Buzi River basin. Finally, the study shows that decisions made on introduction of environmental water requirements downstream the river, affect also the potential water consumers upstream, because of the interlinked system.

As the Buzi River basin is a moderately modified area, with few water using activities, the impact of environmental water requirements on water consumers is assumed to be relatively low. However, if taking future development into account, potential water consumers are likely to be affected, why studies such as this should be re-performed as the area develops.

It should be noted that the scenarios developed by the yield model hold uncertainties. The results should therefore be used as a basis for discussion, rather than an assessment of the area. Finally, the results from this project will be analyzed in an economic perspective, which will provide valuable directives to the local water authority for discussions on water allocation.

Keywords: Buzi River basin, Environmental Flow, Environmental Water Requirement, Water Resource Yield Model

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REFERAT

Implementering av miljöanpassade flöden i Buzi avrinningsområde, Moçambique
- **En påverkansanalys baserad på modellen Water Resource Yield Model**

Stéphanie Nicolin

I områden där rent vatten är en begränsad resurs krävs en balanserad vattenförbrukning. Detta kan uppnås genom att varje konsument tilldelas en avvägd andel vatten, i relation till vad som finns tillgängligt i systemet. En balanserad vattenförbrukning bör även innefatta att man låter reservera en bestämd andel vatten åt ekosystemet, med avsikt att upprätthålla en god ekologisk status i området. Dessa flöden, essentiella för floden och dess ekosystem, är vad vi kallar *miljöanpassade flöden*, eller *environmental water requirements*.

Målet med det här examensarbetet var att utvärdera hur vattenanvändarna i ett specifikt avrinningsområde påverkas av att man inför miljöanpassade flöden. Det område som har studerats är Buzi-floden och dess avrinningsområde i Moçambique. En fältstudie har utförts i området, med avsikt att samla vattenkonsumtions- och tekniska data från berörda vattenanvändare.

Analysen är baserad på den sydafrikanska modellen *Water Resource Yield Model* (WRYM), utvecklad för systemanalys av vattenresurser. Modellen bygger på ett vattendistributionssystem, där varje konsument tilldelas en prioritet med syftet att balansera vattenkonsumtionen inom begränsningarna för det specifika systemet.

Resultatet av arbetet visar att andelen tillgängligt vatten för konsumtion skulle komma att reduceras med ca 30 % för att kunna upprätthålla nuvarande ekologisk status i området. Vidare visar resultatet ett tydligt negativt samband mellan mängden genererad vattenkraft och andelen tillgängligt vatten i systemet. Däremot kan slutsatsen *inte* dras att miljömässiga flöden har märkbart reducerande effekt på produktionen av vattenkraft i Buzi-flodens avrinningsområde. Studien visar även att införandet av miljöanpassade flöden nedströms påverkar de potentiella vattenanvändarna uppströms, p.g.a. de sammanlänkande flödena i avrinningsområdet.

Mot bakgrund av att Buzi avrinningsområde är ett måttligt utvecklat område, med få storskaliga vattenanvändare, antas påverkan på vattenanvändarna från miljömässiga flöden vara låg. Däremot kan framtida vattenanvändare sannolikt påverkas, varför studier som denna bör upprepas i takt med att området utvecklas.

Det bör påpekas att de scenarier som har studerats med modellen innehar stora osäkerheter. Resultatet i rapporten ska därför ses som underlag för diskussion snarare än en utvärdering av området. Slutligen, resultatet från det här projektet kommer även att analyseras ur ett ekonomiskt perspektiv, vilket kommer att ge värdefulla direktiv till den lokala vattenmyndigheten vid beslut om vattentilldelning.

Nyckelord: Buzi avrinningsområde, Miljöanpassade flöden, Water Resource Yield Model

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PREFACE

This master's thesis was conducted at Sweco Environment during the summer term in 2010. It represents the last part of the MSc program in *Aquatic and Environmental Engineering* of 30 ECTS at Uppsala University. The studied subject is within shared water resources as it focuses on the impacts of environmental water requirements, on water consumers in the Buzi River basin in Mozambique. The major part of the project was carried out during two months in Pretoria, in South Africa. With the purpose of collecting necessary information and data regarding the Buzi River basin a field study was conducted to Mozambique, in mid June 2010.

The official supervisor of this study was Rikard Lidén, South Africa Area Manager, at Sweco Environment in Pretoria. Per Olof Seman was the supervisor in Stockholm, at the head office of Sweco. The subject reviewer was Professor Lennart Strömquist at the Programme for Applied Environmental Impact Assessment, Department of Social and Economic Geography at Uppsala University.

The study was financed by the Uppsala University, the Swedish Association of Graduate Engineers in Sweden, and the Swedish foundation *Petersenska hemmet* for the education of female students in Sweden. I would like to thank the institutions above for without whose financial support this project could not have been realized.

I would like to thank my supervisor Rikard Lidén for all the work you have put in to help carry out this study. Without your hospitality and your network of helpful people, the time in Africa would not have been as successful.

Moreover, I would like to thank the people at the BKS Water Resources office in Pretoria for being so friendly and welcoming. In particular I would like to show my gratitude to Jonathan Schroder who assisted me with the yield model showing great patience. I can not express the value of your feed back during the last part of the project. You have constantly been ready to answer my questions, thank you! Special thanks to Estelle Van Nierk for taking the time to introduce us to new places in Pretoria and for being a support throughout the stay in South Africa.

I am further grateful to the staff at ARA Centro in Beira, assisting us with important local information. Special thanks to Mr Antonio Melembe who guided us from Beira to Zimbabwe and who translated for us in Portuguese during the field study in Mozambique.

Lovisa Lagerblad has conducted another master's thesis in connection with this study. Lovisa and I have spent the part of this project, which was carried out in South Africa and in Mozambique, together. I want to thank you, Lovisa, for the input, support and great moments that you have brought this project. The trip to Africa would not have been the same without you at my side.

Finally, would like to show great appreciation to Louise and Johannes, without your support I would not have gone through the last weeks submitting the report.

Stockholm, October 2010

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POPULÄRVETENSKAPLIG SAMMANFATTNING

Jordens vattenresurser är idag hårt belastade som resultat av den globala utvecklingen. Med begränsad tillgång till rent vatten blir det allt svårare att tillgodose en storskalig efterfrågan, utan att ta ut vad som anses vara ”för mycket” vatten ur ett system. I många fall utgår man från vad som är ekonomiskt fördelaktigt, utan hänsyn till floden och dess ekosystem, varför många vattendrag idag är så hårt belastade att de inte längre rinner ut i haven. En förutsättning för att vi ska kunna nyttja våra sötvattendrag även i framtiden, är att vi kombinerar de ekologiska och de ekonomiska aspekterna vid hantering av vattenresurser.

Våra sötvattenekosystem är beroende av floder med ett visst vattenflöde för att kunna upprätthålla viktiga ekologiska funktioner och en värdefull biodiversitet. När floder regleras störs den naturliga flödesregimen, inte bara ifråga om mängden vatten som passerar i floden, utan även vad gäller frekvensen med vilken vattnet passerar. Risken att förlora hela ekosystem, och med dem värdefulla arter, har länge varit känd, men det är först under det senaste årtiondet som vikten av att bibehålla *ett visst* flöde i floden har uppmärksammats. De flöden som krävs för att kunna upprätthålla en god ekologisk status i flodområdet är de som på svenska kallas för *miljöanpassade flöden*.

I Sydafrika har man uppmärksammat en försämrad ekologisk status på grund av långvarigt och kraftigt belastade vattendrag. Som första landet i världen införde man därför miljöanpassade flöden (engelska: *environmental water requirements, EWR*) i lagstiftningen år 1998. Vetenskapen kring miljöanpassade flöden har utvecklats märkbart sedan1998 och idag finns cirka 200 olika modeller, utvecklade för att miljöanpassa flöden i reglerade floder. Att fastställa flodens miljöanpassade flöde är en komplex och tidskrävande process, eftersom såväl ekologiska som sociala och ekonomiska behov ska tillgodoses. Detta är en anledning till att miljöanpassade flöden endast fastställts för en bråkdel av världens reglerade vattendrag.

Ambitionen med det här arbetet har varit att skapa ett underlag för diskussion om införande av miljöanpassade flöden i reglerade flodområden. Syftet har varit att utvärdera påverkan av miljöanpassade flöden på storskalig vattenkonsumtion i ett specifikt avrinningsområde i Moçambique. Påverkansanalysen har främst fokuserat på andelen tillgängligt vatten och genererad vattenkraft i det specifika systemet, efter införandet av miljöanpassade flöden. Tre vattenanvändare ingår i studien; två vattenkraftverk och ett bevattningssystem för sockerrörsplantage, belägna i Buzi-flodens avrinningsområde i centrala Moçambique.

Tillvägagångssättet under vattenresursanalysen bestod i att utvärdera systemets vattensörjande kapacitet i relation till nuvarande efterfrågan på vatten och existerande vattenreglerande infrastruktur. Analysen är baserad på den sydafrikanska modellen *Water Resource Yield Model,* ansedd att vara det främsta verktyget för systemanalys av gränsöverskridande flodområden i *SADC* (*South African Development Community*) *regionen*.

För att kunna utföra vattenresursanalys enligt teorin krävs omfattande mängder information och data på studieområdet, varför en fältstudie var förlagd till Buzi-flodens avrinningsområde i mitten av juni, 2010. Genom intervjuer med vattenkonsumenter och myndigheter i regionen kunde vattenkonsumtions- och tekniska data insamlas för simulering av åtta olika scenarier.

Resultaten av analysen visar att andelen tillgängligt vatten för konsumtion skulle komma att reduceras märkbart vid införande av miljöanpassade flöden. Med avsikt att behålla den nuvarande ekologiska statusen i området skulle införandet av miljöanpassade flöden vid

Chicamba-dammen komma att reducera andelen tillgängligt vatten med 30 %, jämfört med dagsläget. Detta motsvarar cirka 25 % av den årliga medelavrinningen i området. En sådan reduktion skulle dock inte vara märkbar för dagens vattenanvändare, eftersom det aktuella avrinningsområdet är relativt underutvecklat med få storskaliga uttag av vatten.

Analysen visar vidare att systemets kapacitet att producera vattenkraft knappt skulle påverkas vid införandet av miljöanpassade flöden. Det har även visat sig att den begränsande faktorn vid vattenkraftsproduktion *inte* utgörs av risken att ta ut för mycket vatten ur systemet, utan av kravet på leveransförsäkring av elektricitet (ca 95 %).

Då miljöanpassade flöden introduceras vid vattenkraftsproduktion bör såväl ekologiska som ekonomiska aspekter utvärderas vid placeringen av flödet. I den här studien har två alternativa placeringar av det miljöanpassade flödet från en vattenkraftstation undersökts. Resultatet understryker vikten av att granska de ekologiska effekterna av den föreslagna placeringen, ställt i relation till förtjänsten i genererad vattenkraft, för att uppnå ett väl placerat flöde också vad gäller den ekonomiska aspekten. Lösningar som inte är ekonomiskt hållbara blir ju heller sällan långvariga.

Det här arbetet har visat hur man med relativt enkla analysmetoder kan utvärdera vattenresurskapaciteten för ett avrinningsområde för nutida användning, men också för framtida utveckling. Vattenresursanalys borde vara ett obligatorium i vattenresursförvaltning för att världens sötvattenekosystem ska kunna bevaras, trots en intensiv samhällsutveckling med allt högre krav på våra vattendrag.

ACRONYMS AND DEFINITIONS

AFDB African Development Bank

AoS Assurance of Supply

ARA-Centro Regional Water Authority (Mozambique)

BLF Base Load Factor

DC Dam Capacity

DSL Dead Storage Level

DWA Department of Water Affairs

EDM Elitricidade de Mozambique

EWR Environmental Water Requirement

FSL Full Supply Level

IUCN International Union for Conservation of Nature

km^2 Square kilometres

LF Load Factor

MAE Mean Annual Evaporation

MAP Mean Annual Precipitation

MAR Mean Annual Runoff

MARf Mean Annual Runoff factor

m.a.s.l. Meters above sea level

Mm^3/a Million cubic metres per annual

MWc Mega Watt Continuous

PLF Peak Load Factor

PES Present Ecological Status

SADC Southern African Development Community

SWCSP Shared Watercourses Support Project

TWE Tail Water Elevation

WRYM Water Resource Yield Model

Yf Firm Yield

Ecosystem "A complex system formed by the interaction of a community of organisms with its environment" (World Bank, 1993).

River Basin "A geographical area determined by the watershed limits of a system of water, including surface and underground water, flowing into a common terminus" (World Bank, 1993).

1. LIST OF CONTENTS

1 INTRODUCTION

Because of increasing demands of fresh water, rivers become regulated worldwide with the purpose to meet the requirements of the global development. With limited access to adequate water it is difficult to accommodate large- scale water demands without exposing rivers to over abstraction. Today there are many rivers that no longer flow into the ocean, as a result of river degradation. In fact it is said that *one major river out of ten no longer flow into the sea for several months of the year*. Water shortage and shared water resources exaggerate water conflicts between people since when it comes to fresh water, everybody lives downstream of someone else.

The Buzi River is a shared watercourse between Mozambique and Zimbabwe, at the south east coast of Africa. At the initiative of the Mozambican and Zimbabwean government, the Buzi River basin became the study area of the consultancy assignment ("The Buzi Project") of Sweco, in mars 2010. The project is part of the *Shared Watercourses Support Project* (SWCSP) for Ruvuma, Buzi and Save river basins, prepared by the *Southern African Development Community* (SADC) and the *African Development Bank* (AFDB). Parts of the consultancy objective is to "develop a Joint Integrated Water Resources Management Strategy", which includes identification of water demands, as well as an analysis of the potential future development of the river basin.

The Buzi River basin is today moderately developed in terms of water using activities. As competing water demands within the economical sector will increase, the situation requires rational decisions on how to allocate water within the limits of availability. The future question will be how to allocate water between various demand centres without threatening the ecosystem of the river. Introducing environmental water requirements successively, when admitting new water infrastructure, could be one way to maintain "river health".

In context of the implementation of environmental water requirements, different interests come together for the location of the environmental water releases. Should they be located to benefit the water consumer or the environment in the area?

1.1 RESEARCH OBJECTIVES

The objective of the study was to perform an impact analysis of environmental water requirements, from a water using perspective. The study is based on the Buzi River basin in Mozambique and focuses on the water resource and hydropower potential of the system.

The evaluated scenarios were performed and evaluated by the South African Water Resource Yield Model (WRYM). As the model requires a great portion of hydrological and operational data of the river basin and from its water consumers, a field study was conducted to the Buzi River basin.

The analyzed water consumers were two hydropower generating dams and one irrigated sugar cane plantation. The effects from implementing environmental water requirements are presented in terms of water resource capability (firm yield), hydropower capability (firm power), assurance of supplied hydropower and maximum irrigation area.

Within the objective of the study is also to evaluate the role of the *present ecological status* of the catchment, due to implementation of environmental water requirements.

The main objective is undertaken with the purpose to answer the following questions:

- When implementing environmental flow releases, what is the impact on water consumers in terms of:

  - Water resource capability?
  - Hydropower generating capability?
  - Assurance of supplied hydropower?
  - Available irrigation area?

- What are the effects in available water resources for consumptive use when increasing the electrical power demand?

- How can the location of the environmental flow release affect the hydropower capability of the system?

- In relation to the questions above, what are the effects of changing the determination of the present ecological status of the sub-catchment?

1.2 PROJECT LIMITATIONS AND SOURCES OF ERRORS

The study is limited to environmental water requirements and the impact of their introduction in terms of available water resources and hydro electrical potential for water using activities. The analysis does not involve environmental aspects due to environmental water requirements, a subject evolved and presented in a parallel thesis, performed by Ms. Lovisa Lagerblad (Lagerblad, 2010).

The geographical itinerary for the field study was limited to the Buzi River basin, because of the possibilities of getting around by car. As the area is moderately developed and sometimes very remote, only two out of three water consumers could be visited during the field study. As some required data was missing, contacts had to be made with stakeholders in the area, in order to complete data.

The possibilities of collecting historical flow data for the catchments were limited because of the given budget and time frame. Therefore parts of the annual flow data (*monthly point rainfall* and *monthly reduction in runoff due to afforestation*), required by the model, were approximated to the corresponding data of nearby areas (for details, see Appendix B). The approximations are considered realistic, based on previous experiences with the yield model (Schroder, 2010, pers. comm.).

For the purpose of this study, environmental flow data based on present ecological status was required. The determination of both the present ecological status and the environmental flow requirements was performed by Ms Lovisa Lagerblad in a thesis parallel to this one. The limitations within the determination of environmental flow requirements are presented in the thesis report, *Assessment of environmental flow requirements in Buzi River basin, Mozambique* (Lagerblad, 2010).

The Water Resource Yield Model is not capable of running simulations while changing given configurations over time. It only operates for a certain “time-slice”, keeping demands and operating rules on a constant level through the simulation period (McKenzie et al., 1998). This is not always consistent with reality and should therefore be considered when looking at the results.

Only annual demand variations were included in the analysis of environmental water requirements. Inter-annual demand variations such as seasonal changes or changes over day and night, were excluded due to the vast amount of data that would have to be collected. Furthermore, all scenarios were analyzed based on historically time series due to the limited time frame. This is an important notice as the results based on historically time series are constrained to, and highly influenced by, the record length available for the analysis.

Finally, the WRYM model is based on linear program techniques, why all inputs have to be described as numbers of linear segments. This is considered a limitation of the model, as it also requires non-linear relationships such as volume, elevation, tailwater rating curves and efficiency curves.

2 BACKGROUND

2.1 INTRODUCING ENVIRONMENTAL WATER REQUIREMENTS

There is globally an increasing recognition that river discharge modifications have had adverse impacts on river ecosystems, reducing the natural flow regime of the river system (Megan Dyson et al. 2003). Human interventions such as dams, channels, agriculture abstractions and urban supply infrastructure, have been implemented without consideration of the natural flow regime of the river. When changing the total flow regime of the river it can loose its natural behaviour with affects on size and frequency of floods, as well as on the seasonality of floods. This has negatively affected the ecological and hydrological services, provided by the water ecosystems. To help prevent river degradation, flow modifications need to regard these essential and water dependent ecosystem services, and keep sufficient water amounts in the river. These extra amounts of water allocated to the river and its ecosystem functions are the *Environmental Water Requirements*.

Defined per IUCN (International Union for Conservation of Nature) (Dyson et al., 2003), an environmental water requirement is:

"The water regime provided within a river, wetland or coastal zone to maintain ecosystems and their benefits where there are competing water uses and where flows are regulated".

The science of environmental water requirements (EWR) is well discovered in South Africa, and inter-basin transfers and large dams have there been emphasized as solutions to implement environmental water requirements for years. In South Africa, EWR has been enshrined in legalisation (National Water Act, No. 36 of 1998) since 1998 (Department of Water Affairs, 1998).

Figure 1 *A water abstraction pumping water out of the Buzi River to irrigate the Buzi sugar cane plantation.*

There is a circulation of various terminologies of environmental water requirements, which **can be misleading**. Examples of synonymous terminologies are *Environmental Flow Requirements* (EFR) (used in Mozambique) and *Environmental Water Demands* (EWD). There exist other terms, although they are not all synonymous to the mentioned alternatives above. Without going deeper into the definitions of the different terminologies, the term *Environmental Water Requirements* (EWR) is the term to be used further on in this report, in order to avoid misunderstandings. It is the most held terminology in South Africa, where the water resource analysis for this thesis was conducted. When referring to what is known as *Environmental Flows*, the terminology of *Environmental Water Releases* or simply *Environmental Flows* will be used in this report.

Box. 1. *Synonyms for the terminology of environmental water requirements*

2.2 PRESENT ECOLOGICAL STATUS WITHIN EWR

The present ecological status (PES) is an indicator of the health of the river basin. The purpose of establishing the present ecological status of the reserve is to define the status of several biophysical components of the river relative its natural condition, its "reference scenario". The process of determining the present ecological status of a reserve is called *EcoClassification* and is required within any environmental water requirement methodology (Kleynhans & Louw, 2007).

The South African eco-classification system, used to define the present ecological status of the reserve, is based on an A to F category scale, developed by DWA[2] (Kleynhans & Louw, 2007) (Table 1). The category "A" refers to an "unmodified reserve" whereas category "F" refers to an "extremely modified reserve". There are notional boundaries between the categories, and a given area could potentially have membership of two categories. For these situations there are "boundary categories" in between the six main categories, denoted as A/B, B/C etc. The ecological aim is always to try to maintain or upgrade the PES of the reserve, when implementing changes that affects the river.

Table 1 *The six categories within the present ecological status (modified from Kleynhans & Louw, 2007).*

Present Ecological Status (PES)	Category description
A	"Unmodified, 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.

[2] Department of Water Affairs, South Africa

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 determination of the present ecological status of the reserve within a river system is a complex and time-consuming process. It takes many aspects into account, such as level of bank erosion, flow modification and water quality. In South Africa the responsibility of determining which category a river falls into lies within the Department of Water Affairs, after consulting with stakeholders in the area (Kleynhans & Louw, 2007).

2.3 WATER RESOURCE ANALYSIS

The overall purpose of water resource analysis is to develop and approve the design and operation of water resource systems. It is considered the most complicated, but also the most important, task in water management (Votruba, 1988). The approach of water resource analysis is to compare water requirements and water infrastructure with available water in the system. If possible, it is of great importance to also include future potential conditions for the purpose of protecting the aquatic ecosystem from over abstraction.

In Southern Africa, international water resource agreements for transboundary rivers are based upon system analysis models for water planning and allocation (D. Juizo et al., 2008). The system analysis models are developed to propose the best water resource management strategy, maximizing the benefits for the water consumers. The South African *Water Resource Yield Model* (WRYM) (Van Rooyen et al., 2003) has been extensively used throughout the area over the last 20 years, and it is the preferred model tool for system analysis of international river basins in the SADC region (Juizo et al., 2008). WRYM was developed in 1984 by the South African Department of Water Affairs in cooperation with the BKS consulting company in South Africa.

WRYM is based upon a penalty system, issued from the priority of water supply given by the user. One of the strengths of the model is that the user can change the operating rules through external system data files, instead of having to make changes into the actual source code of the system (Van Rooyen et al., 2003). Although it is the most recognized model in South Africa it has been questioned because of its complexity and limited transparency (Juizo et al., 2008).

Examples of alternative tools for system analysis of river basins in Southern Africa are *Mike Basin* and the *Water Situation Assessment Model* (WSAM) (Mallory et al., 2008). Mike Basin is a GIS-based[3] simulation package developed by DHI (Water Environment Health), which has become extensively used throughout the world (Mallory et al., 2008). WSAM is also developed for the purpose of modelling South African water resource conditions, but unlike the two other models it is not capable of interact with other models or pre-processors.

2.4 WATER RESOURCE ANALYSIS INCLUDING HYDROPOWER GENERATION

The yield of a water resource system may be determined either in terms of its water resource capability or its hydropower generation potential. As this study include two hydropower generating companies an introduction to hydropower generation is considered relevant.

The principle of extracting energy from hydropower is based on the availability to make use of potential energy. The power plant is built somewhere along the river, where there is a difference in elevation. The potential energy lies in the high-level water. As the force of falling water turns the turbines in the plant, the turbines turn the generator which produces electrical energy. Potential energy has been converted to electrical power. The water is then returned to its original furrow, a bit downstream of the inlet. The area in between the inlet and the outlet usually becomes a dry area, a so called dry furrow. The latter can be considered an environmental problem, since the ecosystems with its certain requirements of water no longer have the same access to the resource.

2.4.1 The power plant

Figure 2 illustrates the typical hydroelectric power plant. The amount of extracted power depends on the water flow and the difference in water surface elevation. The difference in water surface elevation between the reservoir and the tail water is called the *Designed Net Head* (or *head*) and is proportional to the amount of potential energy. Other characterising elevations, that have to be taken into account when modelling hydropower in the yield model, includes the *Full Supply Level* (FSL), the *Dead Storage Level* (DSL) (or the *Low Supply Level,* LSL*)* and the *Tail Water Elevation* (TWE), all in units of meters. In terms of capacity, the reservoir storage, the surface area (at FSL), the turbine capacity and the generator capacity are other important technical characteristics of the power utility.

In context of calculating the firm power, a *minimum net head* and a *maximum net head* have to be defined to identify the range of allowable operating heads for the turbine. The minimum net head is the LSL subtracted with the tail water elevation, and the maximum net head is the FSL subtracted with the tail water elevation

[3] Geographic Information System (GIS)

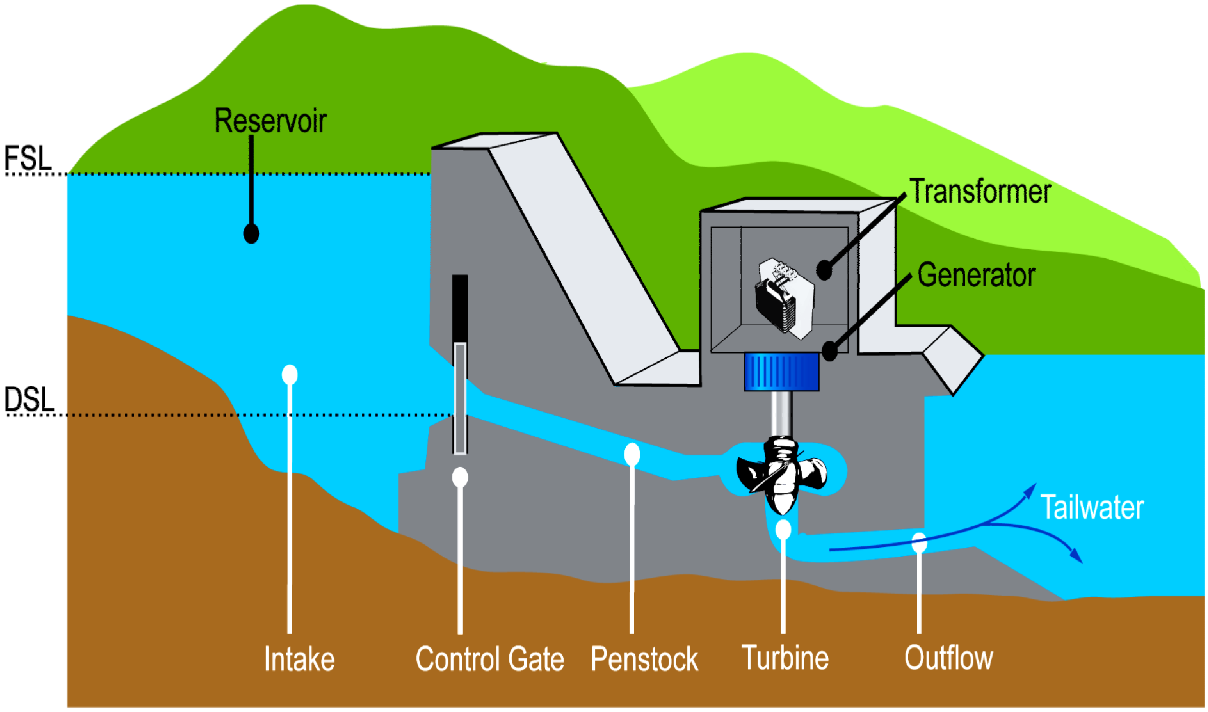

Figure *2 The typical hydropower plant with its various technical characteristics (author's illustration).*

2.4.2 Water releases through the hydropower plant

The hydropower reservoir acts as a buffer for the system. The reservoir stores water during periods with high flows for periods when it is more profitable to sell electricity. On occasions when the inflow exceeds the capacity of the dam, i.e. when floods occur, water is spilled through the spill channel of the power plant. In general, short-term reservoirs do not have the buffer capacity as they are too small to control the flow of the river. In context of high flows they have to spill water at all times (Schroder, 2010, pers. comm.).

Releasing extra amounts of water for environmental purposes, would lead to a reduction of the amount of water that can be used for production. This is obviously associated with costs for the producer as the hydro electrical capacity decreases. For this reason, spilling is theoretically only occurring when the average water flow exceeds the capacity of the dam.

3 STUDY AREA

3.1 BUZI RIVER BASIN

Buzi River is one of 104 identified rivers in Mozambique. It is recognized as one of the more important watercourses, shared between the two countries Mozambique and Zimbabwe. It has a catchment area of approximately 28,980 km^2 of which a major part, of approximately 26,000 km^2 (90%), is located in Mozambique, and approximately 3,000 km^2 (10%) is located in Zimbabwe (Sweco, 2010).

Buzi (or "Budzi" as it is called in Portuguese) River flows eastwards, towards the Indian Ocean, and covers parts of two provinces, Sofala and Manica, in central Mozambique. Towns of importance within the Buzi River basin in Mozambique are Chimoio (the capital of Manica province), Buzi and Villa de Manica.

The river system consists of three major rivers; the Buzi River, the Lucite River and the Revue River (Figure 3). Two hydropower schemes, Chicamba and Mavuzi, are considered the most important water activities, located at the Revvue River. Except for hydropower, the area is largely reliant on small-scale agriculture. The mid and lower reaches of the Buzi River basin have so far been moderately modified (Sweco, 2010).

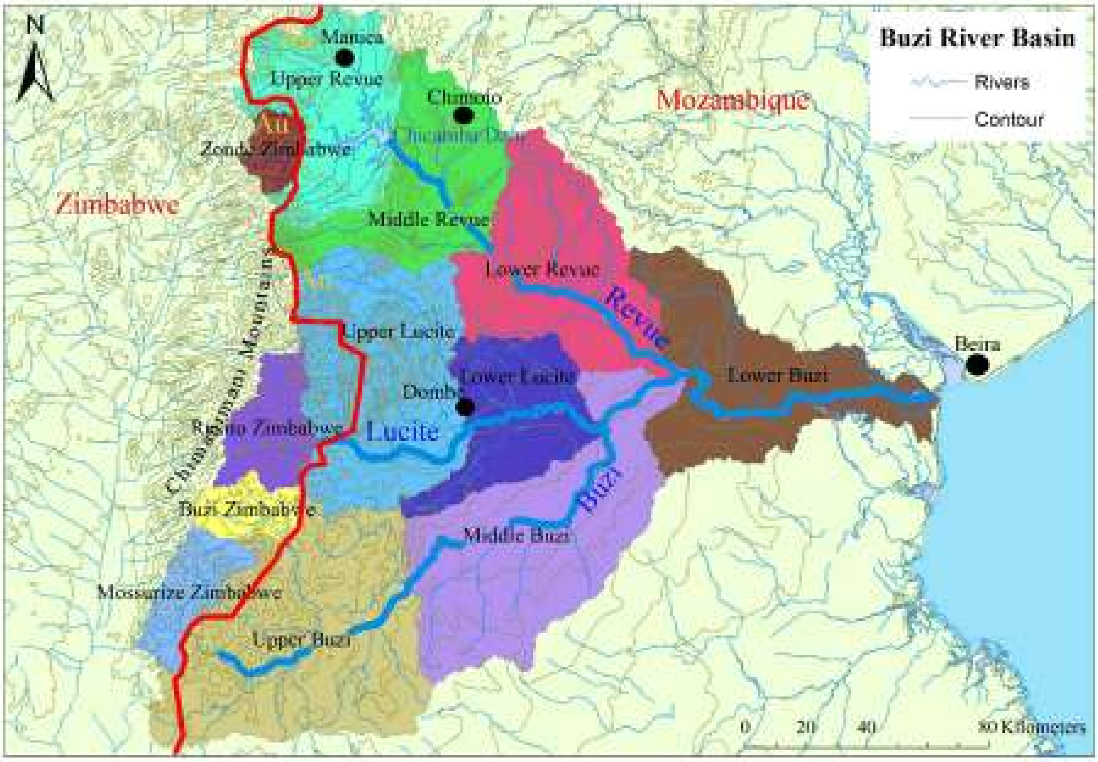

Figure 3 *Buzi River basin divided into sub-basins with the major river basins (Revue, Lucite and Buzi) marked with a blue line (map from Lagerblad, 2010).*

3.2 CATCHMENT HYDROLOGY

The Buzi River basin is exposed to a high variability in climate, as are large parts of the southern African east coast. Both the mean annual precipitation (MAP) and the mean annual potential evaporation (MAE) vary widely from the inland areas to the coast. The highest levels of mean annual precipitation are measured over the Zimbabwean sub-basins, with approximately 1200-1300 mm/yr, while a lower value of 900 mm/yr is measured over the eastern areas, at the coast. The mean annual evaporation is on the contrary relatively low over the Zimbabwean sub-basins, with approximately 900 mm/yr, compared to the coastal areas with approximately 1300-1400 mm/yr (Sweco, 2010).

The high variability in climate causes significant influence on the amount, timing and frequency of the precipitation. The area has experienced several floods during the last decades with the most recent ones in 2007, 2008 and in March 2010.

As seen in table 2, the mean annual runoff (MAR) also varies greatly over the area. Common for the Zimbabwean areas are relatively low values at approximately 200-500 Mm^3/a, while the northern parts of the Buzi basin, with Upper and Middle Revue, are measuring values of 940 Mm^3/a and 750 Mm^3/a, respectively. The Lower Buzi sub-basin, at the coast, is measuring 320 Mm^3/a as MAR (calculated from Sweco route flows, August 2010).

Table 2 *Catchment hydrology data for Buzi River sub-basins based on the years 1954- 1999 (Olof Persson, 2010, pers. comm.).*

Main River	Sub-catchment	Area [km^2]	MAP [mm/yr]	MAE [mm/yr]	MAR [Mm^3/a]
BUZI	Buzi Zim	541.0	1200	~900	~260
	Mossurize Zim	788.9	1200	~900	~380
	Other Zim 1	390.1	1200	~900	~190
	Upper Buzi	4469.0	1100	~1200	~1000
	Middle Buzi	3872.0	900	~1300	~420
	Lower Buzi	3269.0	900	~1400	~320
LUCITE	Rusitu Zim	969.1	1300	~900	~550
	Other Zim 2	644.9	1400	~900	~420
	Upper Lucite	3191.0	1200	~1200	~1030
	Lower Lucite	1892.0	1000	~1400	~250
REVUE	Zonue Zim	383.8	1300	~900	~220
	Other Zim 3	133.7	1200	~900	~60
	Upper Revue	2339.0	1200	~1000	~940
	Middle Revue	2474.0	1100	~1050	~750
	Lower Revue	3626.0	1100	~1400	~640

3.3 REGIONAL WATER ADMINISTRATION

At regional level there are five different Regional Water Administrations (ARA: s) acting in Mozambique. The regional administrations have the responsibility to prepare and implement hydrological basin development plans, maintain and operate hydrological infrastructure (such as dams and waterways), keep a register of water consumers, collect water user taxes and fees, issue water use, effluent licenses and operate the hydrological measurement network (Sweco, 2010). ARA Centro was established in 1997 and it is the water administration unit for the Buzi River basin. The overall objective for the regional water administrations is to be self-sufficient by the taxes from the water users in the region. This is not yet achieved for ARA Centro. ARA Centro relies up to 30 % on external financial supports since barely 70 % of the water fees are collected from the water users (Fobra, 2010, pers. comm.).

3.4 BUZI RIVER WATER CONSUMERS

In Buzi River basin there are five main water consumers, of which three users are paying the mandatory water tax to the regional water administration, ARA Centro (Carlitos, 2010, pers. comm.).

The upper part of the river basin, consisting of the Revue river sub-basins, is regarded as the most developed part, due to the hydropower production. The area is exposed to land erosion, as a result of the massive artisanal gold mining above the Chicamba dam. The Lucite River is considered the second most developed river. Even though there are no dams along the Lucite River, mango, banana and sugar cane plantations are relatively common. The least developed river, in terms of water using activities, is the Buzi River in the southern parts of the basin.

For the production of electricity, Mozambique has four main hydropower stations. The Chicamba and Mavuzi dams are supplying the interconnected network of the central and northern regions of Mozambique, and are particularly important to the central regions where they represent the main supply of electric power.

Chicamba dam
The Chicamba dam is operated by the Mozambican power utility *Electricidade de Mozambique* (EDM) and it is mainly dedicated to the production of hydropower. The Chicamba reservoir is located on the Revue River (in the Upper Revue sub-basin), near the border of Zimbabwe. It has a storage capacity of approximately 2000 Mm^3 at its maximum, with a corresponding surface area of 120 km^2 (EDM, 2010). In addition to power generation, the reservoir is also used for fishery, recreation and urban supply by the people living in Chimoio (Carmo Vas, 2010, pers. comm.).

Mavuzi dam
The Mavuzi hydropower dam is located about 60 km downstream of the Chicamba dam. It provides a significantly smaller storage capacity of approximately 1, 8 Mm^3 (EDM 2010), compared to the Chicamba dam. Although the Mavuzi dam provides less water, it is designed using a larger net head why the generating capacity is essentially higher for the Mavuzi dam than for the Chicamba dam (for details on technical characteristics see *Appendix C*).

Buzi Company
One of the major agro-industrial companies in the area is the Buzi Company, an irrigated plantation for sugar canes. The Buzi Company is located in the Lower Buzi sub-catchment (Figure 3). Its irrigation system was built for the cultivation of sugar canes, with an industry producing sugar and alcohol. The bulk of the Portuguese-owned business closed somewhere in the early 90^{th} century and large fields have been lying idle since, with the factory slowly becoming obsolete (Figure 4). There are still sugar cane plantations at the Buzi irrigation fields, even if to a smaller extent. Today the company sells most of the annual harvest to the Mafambisse sugar cane estate, north of the Buzi Company (Carlitos, 2010, pers. comm.).

Figure *4 The industry of Buzi Company, once producing sugar and alcohol, is now days in great need of rehabilitation.*

4 METHODOLOGY

The impact analysis of implementing environmental water requirements in the Buzi River basin was divided into three main steps; *Field study*, *Model setup* and *Yield simulations*.

4.1 THE FIELD STUDY

The starting point of the impact analysis was to get information for the set-up of the water resource yield model schematic flow network. To be able to identify and characterise the physical features of the river system such as denoting rivers, reservoirs and abstraction works, information was collected through a field study at the Buzi River basin, in central Mozambique.

Together with a hydrologist from the regional water authority ARA Centro, a four day long field trip was conducted in the middle of June 2010. Also another masters thesis student from Uppsala University, Lovisa Lagerblad, was accompanying, collecting hydrological information for the determination of the present ecological status of the sub-catchments within the basin.

The itinerary started in Beira, going west with the Revue River to the border of Zimbabwe (Figure 3). The main purpose of the field trip was to visit water consumers, authorities and relevant hydrological measurement stations. Through interviews with people connected to the water using activities, necessary data on water consumption were collected. In situations when people only spoke Portuguese, the hydrologist was able to assist as an interpreter.

4.1.1 The selection of water consumers

For the selection of water consumers, the ambition was to study different water-related activities. Another selection criterion was the physical location of the water user, since parts of the river basin are very remote and difficult to access by car. Also the level of water consumption was considered. The guiding principle was; the higher level of water consumption, the higher impact of flow modifications and the more distinct results for the water resource analysis.

There were three different water using activities chosen for the study (for geographical locations see figure 3):

1) Water user: Chicamba Hydropower Scheme
   Location: Upper Revue sub-basin

2) Water user: Mavuzi dam
   Location: Middle Revue sub-basin

3) Water user: Buzi Company: An irrigated sugar cane plantation
   Location: Lower Buzi sub-basin

4.2 MODEL SET-UP

The second part of the EWR impact analysis consisted in setting up the schematic flow network for the river basin in the Water Resource Yield Model. This was essentially done by connecting various system components into a visual network in the WRYM-IMS (Information Management System) interface. This step included defining large amounts of operational and hydrological data for all network features and was considered the most time consuming part of the study.

4.2.1 Catchment hydrology

A part of the main hydrological flow data for the sub-catchments was presented by Sweco, for the purpose of executing yield analysis of Buzi River basin. Mr Olof Persson, consultant at Sweco, was assisting with necessary data for the mean annual runoff. The Water Resource Yield Model requires all catchment hydrology data to be converted into naturalised flow data. Naturalised flows represent the river without any human made development, the reference scenario. To obtain the naturalised flows for Buzi River, the South African *Pitman model*[4] was assumed to give sufficient accurate results.

There were four sets of hydrological data required as main input for the yield modelling;

- *Monthly naturalised incremental flow* (**INC**)
- *Monthly point rainfall* (**RAN**)
- *Monthly diffuse irrigation demand* (**IRR**)
- *Monthly reduction in runoff due to afforestation* (**AFF**)

[4] The Pitman Model was first developed in 1973 and has now become one of the most widely used monthly time-step rainfall-runoff models within Southern Africa (Huges, 2003).

As a majority of the monitoring stations in the Buzi River catchment are remote, hydrological flow data have not been continuously collected for the historic time period used in the WRYM. The monthly point rainfall (RAN) and the monthly reduction in runoff due to afforestation (AFF) have therefore been approximated, using data for geographically close catchments (for details on the approximations, see Appendix C).

Input for the implementation of environmental water requirements were environmental flow data presented as fixed monthly percentage of the mean annual runoff. The environmental flow data was determined by using the South African Desktop Reserve Model (DRM)[5] and managed by Ms. Lovisa Lagerblad. In order to get environmental flow data for a specific catchment, the cumulative MAR was calculated for that area (for details on MAR see Appendix A).

4.2.2 The flow schematic network

Setting up the network for the river system started by linking together junction nodes and channels in the IMS interface. These components are the so-called *basic blocks* and connect water flows into a flow schematic network (Figure5). The nodes were used to connect different flow- types within the network, but they could also perform special functions in the simulations. The channels represent conduits that convey water between nodes within the system, and they model a variety of hydraulic functional features such as canals, river reaches, pipelines and other hydraulic structures.

Other basic blocks used within the WRYM-IMS were the *arcs*. Arcs allow channels to be configured in a certain way so that only particular flows are allowed through them, under the given circumstances. The WRYM model allows use of up to five arcs per channel, although one and two-arc channels were sufficient for the set-up of the Buzi River system. For each arc three data values had to be specified; a lower flow limit (determined equal to zero), an upper flow limit and a so-called *penalty*, associated with each unit of flow passing through a reservoir (for description of penalties, see section 4.2.2).

To include reservoirs in the IMS network their physical characteristics had to be defined including elevation levels, storage capacity and surface area. Other hydrological parameters such as net runoff (contributing to the inflow of the reservoir), evaporation from and rainfall on the water surface, were established as well.

[5] The Desktop Reserv Model is developed (Huges and Hanart, 2003) as a quick estimation method for environmental water requirements for South African conditions.

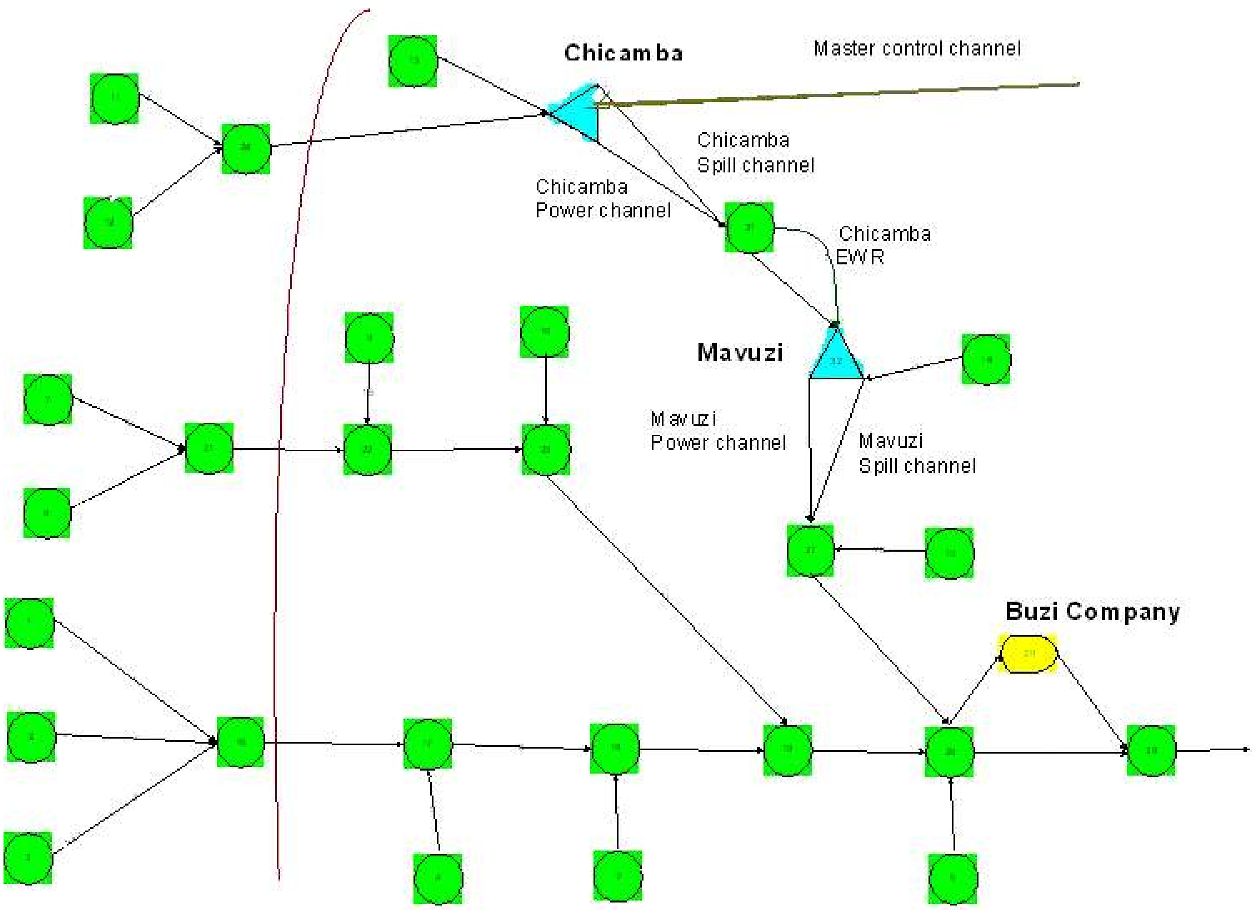

Figure 5 *The Buzi River basin with the analyzed large-scale water consumers, illustrated in the WRYM- IMS. The green dots represent the nodes and the black lines represent flows with directions. The two blue triangles represent the reservoirs of the power plants and the yellow dot represents the irrigation field. The red line illustrates the border between Mozambique and Zimbabwe (illustration by author, recreated version).*

4.2.3 Priority of water supply

Related to the configuration of reservoirs is the set of *operational rules*. The operational rules are based on a priority system for water supply, used by dividing the reservoir into different storage zones with the purpose to control the way the reservoir is being drawn down (Van Rooyen, 2003). The rule system regulates the priority of water supply amongst water consumers and the priority of water use within, and between, reservoirs.

The operational rules are implemented through a mechanism called *penalties* (between water consumers) or *penalty structures* (within the reservoir), assigned to every unit of water that flows through a channel or that is being impounded in a reservoir. The priorities are based on strategic importance and the consequences of not supplying the water user (i.e. in a situation with limited amount of water in a water resource system, it is considered a bigger issue not to generate power from a power system, than not to supply water for irrigation) (Schroder, 2010, pers. comm.). Priorities only apply when there are limited amounts of water left in a water resource system, i.e. in a drought situation, and when the water level gets to (or drops below) the DSL (Figure 2).

For the purpose of this study, fairly common priorities of water using activities were used due to time and budget constraints. From highest to lowest, the priorities were used as follow (Schroder, 2010, pers. comm.):

1. Urban, rural and industrial water use (including hydropower)
2. Ecological water requirements
3. Irrigation

4.3 YIELD SIMULATIONS

The last part of the impact analysis in WRYM consisted in running yield simulations, studying the operational behaviour of the system, verifying results and, if needed, correcting implemented faults.

4.3.1 WRYM outputs

Firm yield
Water resource systems are designed to move water from where it is relatively abundant to where it is needed. The amount of water extracted from such a system is the *yield* of the system (Basson et al., 1994). The yield is likely to vary over time depending on water demand, the level of the system development and climate variability. The *firm yield* is defined as the maximum annual water volume (or yield) that can be abstracted from a reservoir for a given inflow sequence, temporal demand pattern and operating policy. In other words, the firm yield is the capacity of the water resource system, and it is an essential factor to study when making water resource analysis. Firm yield is one of the main outputs of the analysis and has the units of million of cubic meters per year (Mm^3/a).

This particular analysis is based on *historic firm yield* which is one of various measures of water availability in a water resource system.

Firm power
The yield of a water resource system may also be determined in terms of its hydropower generation potential, its so- called *firm power*. The firm power is normally used in units of megawatts or mega watt continuous, depending on how the power utility is operated (Schroder, 2010, pers. comm.). For this specific study the units of mega watt continuous are used as the hydropower activities are considered operated as base load power plants (for details on hydropower units, see section 4.3.5)

Possible irrigation area
For the analysis of the Buzi Company irrigation system, the results were chosen to be presented as maximum irrigation area. This is the utmost possible area that can be irrigated based on the system, the specific crop, the efficiency factor for the irrigation system and the irrigated area, among other factors. The maximum irrigation area is used in the units of hectares.

Assurance of supply
The assurance of supply factor is used when including power generation in the simulated scenarios. It is an indicator of the actual supplied amount of hydropower, related to what is

requested out of the system. The assurance of supply depends on the type of requirements (water or hydropower) and the effect of a failure to supply the requirement. In this study the assurance of supply complement the results of hydropower potential, shown as *firm powe*r.

Since exact figures of assurance could not be established within the limited time frame, standard levels have been used as follows (Table 3):

Table 3 *Commonly used factors for the assurance of supply for water using sectors (Schroder, 2010, pers. comm.).*

Sector	AoS [%]
Urban, industry	95
Irrigation	90

The assurance of supply is linked to the priorities of water supply (section 4.2.3). Higher priority consumers should be given a higher assurance of supply (Schroder, 2010, pers. comm.).

4.3.2 Running simulations

To evaluate the effects of introducing EWR to the Buzi River basin, the simulations were divided into 8 scenarios, within 6 different EWR related situations. The following scenarios were simulated and analyzed in WRYM:

The reference scenario
The reference scenario was used as a reference state when studying the scenarios below. It refers to a state without any environmental water requirements and it is equal to the present situation.

1. Impact of EWR on firm yield
Scenario 1: Firm yield with increasing PES at the Chicamba dam.
This scenario evaluates the specific impact of implementing EWR on the available amount of water (firm yield) of the system. It focuses on the role of the present ecological status (PES) (section 2.2) when implementing EWR, as the simulations are performed with increasing values of the PES, class C/D to class B.

2. Relationship between hydropower generation demand and firm yield
Scenario 2: Firm yield with increasing power generation at the Chiacamba dam.
Scenario 3: Firm yield at Chicamba dam with increasing power generation at the Mavuzi dam.
Scenario 2 and 3 are chosen to evaluate the reltionship between power generation and the amount of water available for consumtive use in the Chicamba dam. These scenarios are issued to get an estimate of the water consumption of the hydropower production, but also to get an idea of how the assurance of hydropower supply is changing when increasing the power production.

3. Impact of EWR on AoS of hydropower
Scenario 4: The AoS at Chicamba with increasing PES.
Scenario 4 was included with focus on the assurance of supply of hydropower, with the intent to simulate a certain level of hydropower generation from the Chicamba dam.

4. Impact of EWR on firm power
Scenario 5: Firm power at Mavuzi dam, with increasing PES for Mavuzi.
Scenario 6: Firm power at Mavuzi dam, with increasing PES for Chicamba.
Scenario 5 and 6 are the only scenarios evaluating the impact in firm power of the system when introducing an EWR. The impact of the PES is shown as the simulations are performed, increasing the class of the PES.

5. Firm power due to location of EWR
Sceanrio 7: Firm power with alternative locations of the Environmental Water Requirement release at the Mavuzi dam.
The purpose of including Scenario 7 was to study possible impacts that the location of an EWR release could have on the systems power generating capability.

6. Impact of EWR on available irrigation area
Scenario 8: Maximum irrigation area with increasing PES at the Buzi irrigation.
The last scenario shows the impact of implementing EWR in terms of irrigation capability of the system.

4.3.3 Yield analysis with historical flow sequences

The yield analysis of a system can be performed based on either stochastically or historically generated time series. In South Africa, the use of stochastically generated flow sequences is the most common practice of modeling water resources systems (Van Rooyen et al., 2003). The results in this report are based on historical flow sequences, with a period length of 46 years, 1954 to 1999.

Both of the flow generating time series has pros and cons. The historical analysis is considered less time consuming, as numerous checks and tests has to be carried out to verify and validate the stochastically generated sequences. On the other hand, historical analysis (alone) can be misleading as the yield (water or hydropower) is highly influenced by the record length available for the analysis. Therefore, when using historical yield analysis it is of great value to specify not only the results, but also the corresponding level of assurance of supply.

4.3.4 An estimate of yield based on dam capacity to runoff ratio

To validate the reliability of results developed by the yield model, an estimation method was used for the calculation of firm yield. The estimation method, used and developed by the BKS consultancy company in South Africa, is based on the relationship between *dam capacity* and cumulative *mean annual runoff* (Equation 4.1). The value of firm yield is given in percentage of MAR based on the relation in equation 1 (equal to the *MAR factor*) and table 4 below.

By comparing the simulated and the calculated value of firm yield, the accuracy of the yield model could be assessed.

$$MARf = \frac{DC}{MAR} \qquad \text{eq (4.1)}$$

Table 4 *The relation between the MAR factor (MARf) and firm yield (Yf) (Schroder, 2010, pers. comm.)*

MAR factor	Yf (in percentage of MAR)
1	0,3-0,35
1,5	0,35-0,45
1,6	0,46

DC *Dam Capacity* [Mm^3]
MAR *Mean Annual Runoff* (calculated from 3 sub-catchments) [Mm^3/a]
MARf Mean *Annual Runoff factor*
Yf *Firm yield [*Mm^3/a]

4.3.5 The hydropower load factor

The hydropower utilities are included in the WRYM scenarios based on different power generating conditions. Since the electricity demand for a power station can vary significantly with time (i.e. during daytime, throughout the week, over the year), hydropower systems are operated on basis of a *load factor* with the purpose to consider these variations. The load factor depends on the systems number of generating hours per every 24 hours, as shown in equation 2 below.

$$\mathbf{LF} = \frac{generated\ hours}{24\ hours} \qquad \text{eq (4.2)}$$

LF= Load factor

The Chicamba dam is normally operated as a "peaking power plant", based on a *peak load factor* (PLF). A peaking power plant is generating at its *maximum installed capacity* few hours of the day. The Mavuzi dam, on the other hand, is considered being a "base load power plant", which implies that it is generating at a lower level of its installed capacity, but for much longer time a day.

As peaking power systems can not be simulated in the yield model, the Chicamba plant had to be simulated as a base load power plant with a continuously generation of electricity, in units of *Megawatt Continuous* (MWc). The hydropower capacity of Chicamba was multiplied with a commonly used factor of 10 % to get the base load power (*McKenzie and Van Rooyen, 1998*).

5 RESULTS

5.1 BUZI RIVER WATER CONSUMERS

The water using activities, located in the Buzi River basin, are connected to each other as shown in figure 6. The Chicamba and the Mavuzi dams are located at the Revue River and the Buzi irrigation system is located at the Buzi River.

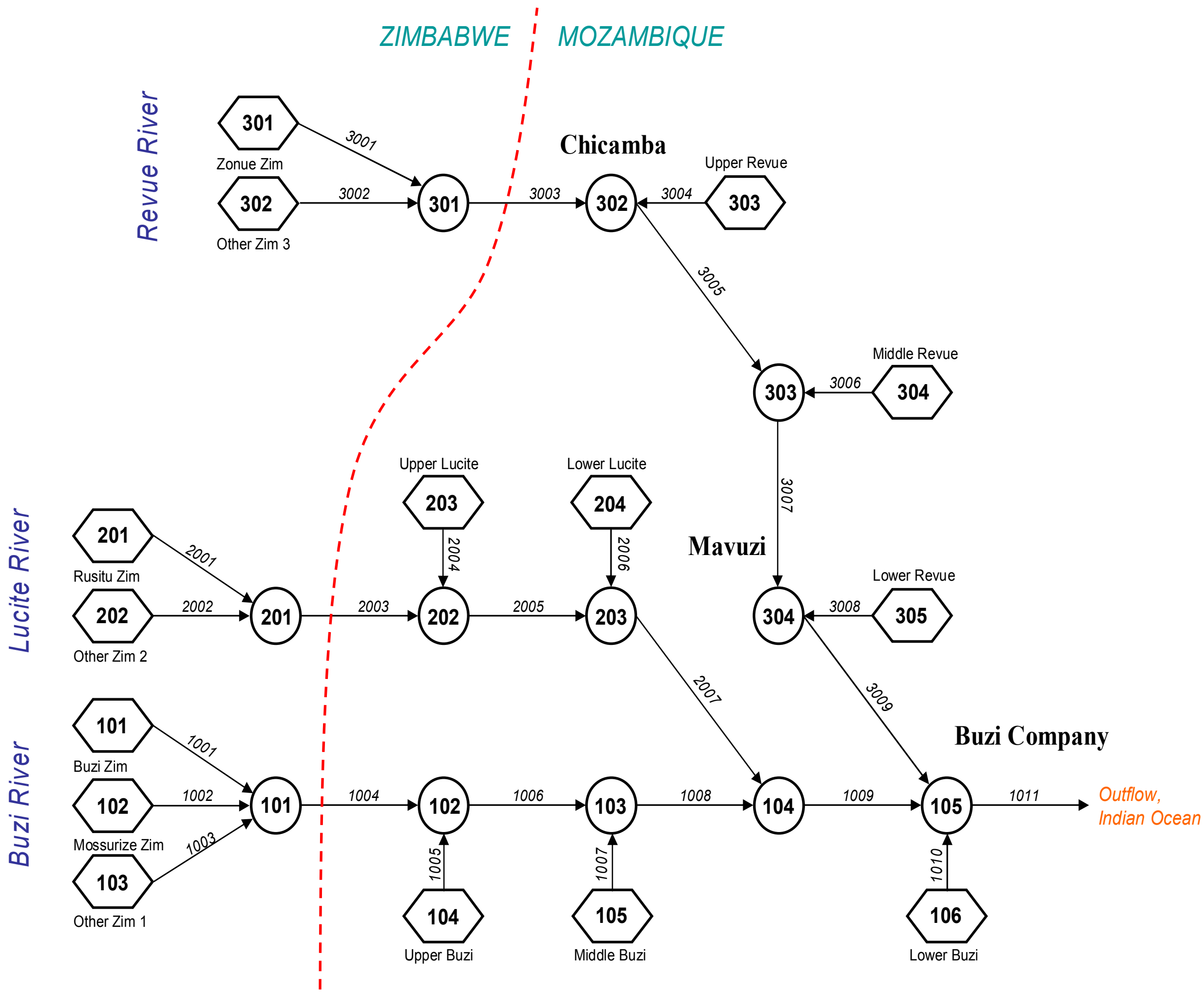

Figure 6 *A flow schematic network diagram for the Buzi River basin, including the water consumers: Chicamba dam (Upper Revue sub-catchment), Mavuzi dam (Middle Revue sub-catchment) and the Buzi irrigation system (Lower Buzi sub-catchment). The hexagonal figures represent the sub-catchments and the nodes represent measurement stations. The red line illustrates the border between Mozambique and Zimbabwe (modified from Sweco, 2010).*

5.1.1 Chicamba Hydro power scheme

The Chicamba dam is located in the Manica province on the Revue River, near the border to Zimbabwe (Figure 3). The hydropower scheme consists of two generating units of 24 MW with an installed capacity of 48 MW (modelled as a base load power plant at 10% of its total capacity, due to software constraints). The reservoir has a total capacity of approximately 2000 Mm^3 with a FSL at 625 m.a.s.l. and a DSL at 590 m.a.s.l. The surface level of the tail water is at 565 m.a.s.l. (*EDM, 2010*) (see Appendix C for technical characteristics on the Chicamba power station).

The hydropower unit was built in two stages. The first stage was finished in 1960 providing storage for the downstream *Mavuzi* power plant, and the second stage was finished in 1973 (Figure 7 and Figure 8).

Figure *7 The Chicamba dam at the Revue River*

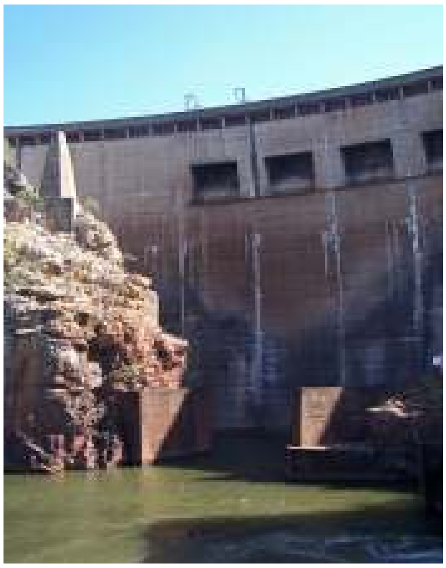

Figure ***8*** *The spillway of the dam*

The Chicamba dam is operated by the Mozambican power utility EDM (Elitricidade de Mozambique), which controls the water abstraction of the dam. Nowadays there is an agreement between EDM and the city of Chimoio that small abstractions of water, for other than power production, are allowed from the dam. These abstractions of water, made by locals, represents only one thousandths of the total amount of water available in the reservoir. Because the hydropower production shall be maximized, EDM will not allow other than insignificant abstractions of water upstream of Chicamba, not at present nor in the future (Lidén, 2010, pers. comm.)

The total catchment area of the Chicamba dam is estimated to approximately 2860 km^2. The cumulative MAR of the Chicamba catchment is calculated to be approximately 1218 Mm^3/a (for details on MAR see Appendix A).

The estimated present ecological status (PES) of the Chicamba catchment area is set to class B/C, which corresponds to a “largely natural” to a “moderately modified” reserve. The class B/C will from now on be referred to as “the recommended class” for the Chicamba reserve.

5.1.2 Mavuzi Dam

The Mavuzi hydropower scheme, about 60 km downstream of the Chicamba dam, is located in the Middle Revue sub-catchment, on the Revue River. It comprises one penstock of 1.47 m diameter and two penstocks of 1.65 m diameter, which convey the water to a powerhouse on the bank of Revue River. The power plant has a total number of five turbines (two at a capacity of 5.5 MW each, and three at 13 MW each) resulting in a combined installed capacity of 50 MW (EDM 2010).

The Mavuzi reservoir has a live storage capacity of 1.8 Mm^3, significantly smaller than the Chicamba reservoir. The dam was built in two stages. The first stage in 1953 resulted in a gravity overflow weir, with a crest elevation at 343 m.a.s.l. (the current LSL). Stage 2 entailed a construction of a highway bridge on top of the overflow weir, increasing the FSL to 345 m.a.s.l., in 1959 (EDM 2010) (for details see Appendix C).

The Mavuzi dam is simulated as a base load power plant, generating power during most hours of the day. The potential generating capacity at the Mavuzi dam is much higher than for the Chicamba dam, as the head measures 160 meter at the Mavuzi dam, but because of a limited cross section of the headrace tunnel, the operation of the power plant is restricted to water flows below 24-25 m^3/s (EDM, 2010)

The total catchment area of the Mavuzi dam is estimated to approximately 5500 km^2. The cumulative MAR of the Mavuzi catchment is calculated to be approximately 2000 Mm^3/a (for details on MAR see Appendix A).

The present ecological status for the area is estimated to class B, considered a "largely natural" area. The class B will be referred to as the "recommended class" for the Mavuzi catchment.

5.1.3 The Buzi Company irrigation system

The Buzi irrigation system, owned by the Portuguese-owned *Buzi Company*, is located in the central province of Sofala in the Lower Buzi sub-basin (Figure 3). The irrigation fields of today are not reaching more than 300 ha, with an annual harvest of 50– 80 ton/ha. It gives an annual production of 15000-24000 tons of sugar canes a year.

The Buzi irrigation system is considered a basic developed system and it can be divided into four mechanisms:

1. The pumping station, which pumps water out of the river.
2. The transfer system, which transports water from the inlet to the reservoir, close to the field.
3. The reservoir.
4. The distribution system, which conveys water in the reservoir to the field.

The distribution system, which characterizes the type of irrigations system, constitutes of irrigation channels (Figure 9). According to the technically responsible at the field, the average water flow through the water pumps is approximately 50-90 m^3/h.

The total catchment area of the Buzi irrigation system is estimated to approximately 22,434 km^2. The cumulative MAR of the Buzi irrigation catchment is calculated to approximately 7170 Mm^3/a (for details on MAR see Appendix A).

The present ecological status for the area is estimated to a class B, corresponding to a "largely natural" area. The class B will be referred to as the "recommended class" for the Buzi irrigation catchment.

Figure 9 *The irrigation system of Buzi sugar cane plantation*

5.2 SIMULATED WATER FLOW SCENARIOS

Following section presents the results from the modelling of environmental flow releases in the Water Resource Yield Model. The results are mainly presented in terms of water resource capability (firm yield), hydropower capability (firm power), assurance of supply of hydropower and maximum irrigation capability of the system.

Eight scenarios were simulated in six 6 different EWR-related situations; all discussed later on in *Analysis of water flow scenarios* (section 6). Below is a brief declaration of the chosen scenarios:

***1.* Impact of EWR on firm yield**
Scenario 1: Firm yield with increasing PES at the Chicamba dam.

***3.* Relationship between hydropower generation and firm yield**
Scenario 2: Firm yield with increasing power generation at the Chiacamba dam.
Scenario 3: Firm yield at Chicamba dam with increasing power generation at the Mavuzi dam.

4. Impact of EWR on AoS of hydropower
Scenario 4:The AoS at Chicamba with increasing PES.

5. Impact of EWR on firm power
Scenario 5: Firm power at Mavuzi dam, with increasing PES for Mavuzi.
Scenario 6: Firm power at Mavuzi dam, with increasing PES for Chicamba.

***6*. Firm power due to location of EWR**
Sceanrio 7: Firm power with alternative locations of the Environmental Water Requirement release at the Mavuzi dam.

7. Impact of EWR on available irrigation area
Scenario 8: Maximum irrigation area with increasing PES at the Buzi irrigation.

5.2.1 Impact of EWR on firm yield

Scenario 1: Firm yield with increasing PES at the Chicamba dam
The first simulated scenario includes an EWR at the inlet of the Chicamba dam (see WRYM illustration of scenario 1 in Figure 5*)*. There is no hydropower generated from any dam in this scenario.

The result shows the impact of the present ecological status (PES) on the amount of available water for consumptive use at the Chicamba dam. Without considering any EWR at the Chicamba dam, the "reference scenario" results in a firm yield of approximately 574 Mm^3/a. As the class of the PES increases more water is required to the river, and firm yield decreases (Figure 10). The simulations are done for the PES going from class C/D to B. According to figure 10, releasing environmental flows based on the *recommended class* B/C, would result in a firm yield of approximately 380 Mm^3/a. That is a reduction of available water of *more than* 30 %, compared to the current situation without any EWR.

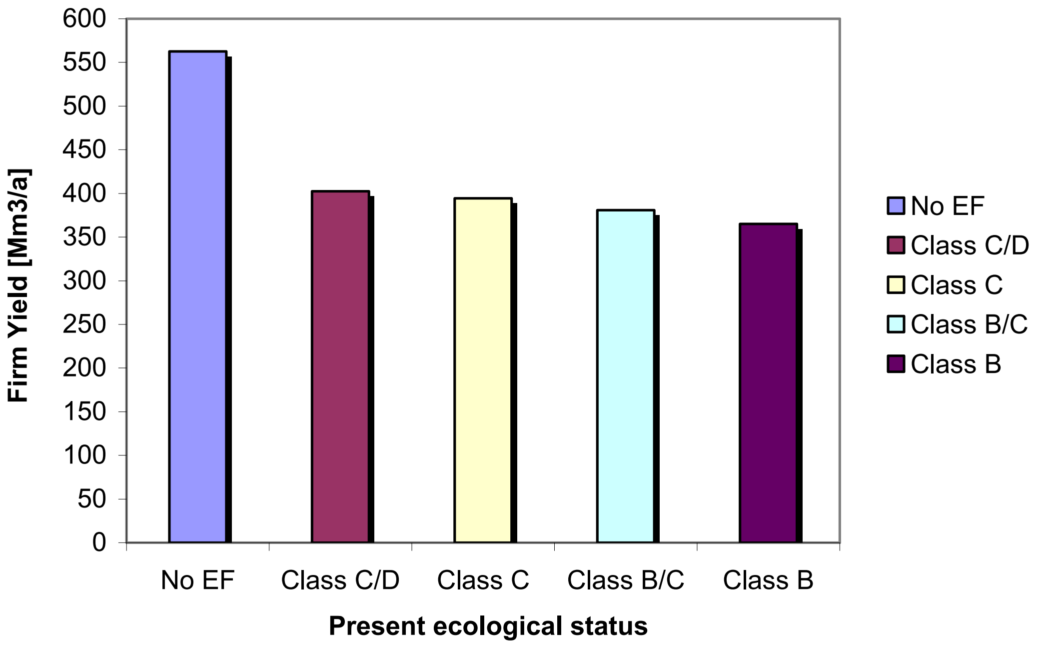

Figure 10 *Firm yield with increasing PES at the Chicamba dam*

An estimate of firm yield based on dam capacity to runoff ratio

The firm yield of the Chicamba dam, without any EWR, was calculated with the estimation method (see section 4.3.3) to be approximately 560 Mm^3/a. This reference value is considered to accord with the result from the yield model, with a difference of 14 Mm^3/a (approximately 2, 4 %).

5.2.2 Relationship between hydropower generation and firm yield

The results in Scenario 2 and 3 are based on simulations of both the Chicamba and the Mavuzi dam, with the purpose to analyze the relation between hydropower generation and firm yield. The following scenarios include hydropower generation at both dams. The results of firm yield are complemented with the results of assurance of supply of hydropower.

Scenario 2: Firm yield with increasing power generation at the Chiacamba dam
For the relation between firm yield and generated hydropower at the Chicamba dam, no environmental water flows was released from the dam. The simulations have been focused on the level of generated power, operating Chicamba as a base load power plant. The range of generated power starts from 0 MWc to its maximum capacity (as a base load power plant) of 4, 8 MWc. As the amount of generated power increases, more water is released through the valves. This amount of water becomes inaccessible in the reservoir for other uses, which shows as a decreased firm yield, in the figure 11.

For the first simulation no power is required, and a maximum yield of 574 Mm^3/a, is attained. When increasing the level of generated power to its maximum, a volume of 260 Mm^3/a is left as firm yield in the reservoir.

Further on, the assurance of supplied hydropower (AoS) at Chicamba is decreasing as the level of the generated power increases (Figure. 11). The commonly used acceptance level for assurance of supply of 95 % is maintained up to a power generating level of approximately 3 MWc. For power generation above 3 MWc, the hydropower assurance drops below the acceptance level. At a power generating level of 4, 8 MWc, the AoS is approximately 64 % (Figure 11).

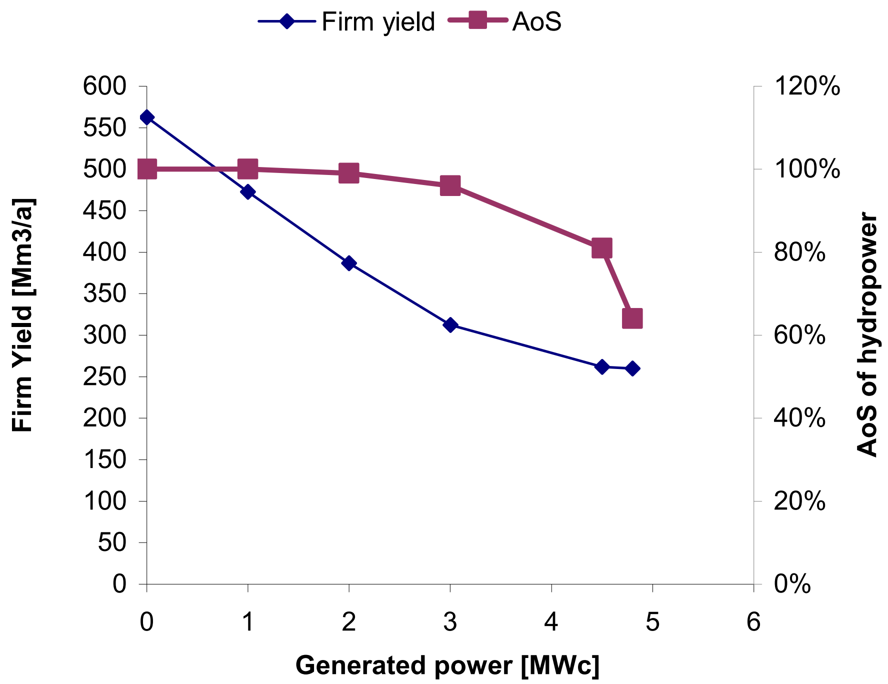

Figure 11 *Firm yield and assurance of supply of hydropower with increasing demands of generated hydropower, at the Chicamba dam.*

Scenario 3: Firm yield at Chicamba dam with increasing power generation at the Mavuzi dam

Scenario three shows firm yield at Chicamba when increasing the hydropower generation at the downstream Mavuzi dam. Following simulations includes two environmental flow releases, one at Chicamba (the one illustrated in figure 5) and one at Mavuzi. The PES regarding the Chicamba EWR release is maintained at recommended class B/C, and the PES for the Mavuzi EWR is maintained at recommended class B. Both the hydropower plants are operating, Chicamba at a constant level of 3 MWc. The range of power simulated at Mavuzi was going from 5 to 20 MWc, with a 5 MWc interval (Table. 5).

Table 5 *Main input parameters for Scenario 3*

Chicamba PES	Mavuzi PES	Chicamba generating power [MWc]	Mavuzi generating power [MWc]
B/C	B	3	5
B/C	B	3	10
B/C	B	3	15
B/C	B	3	20

As illustrated in figure 12, the available amount of water (the firm yield) at Chicamba decreases from approximately 270 to 230 Mm^3/a, with increasing levels of generated power at Mavuzi. The assurance of supplied hydropower at the Mavuzi dam is kept close to 100 % up to a power generating level of 15 MWc. Whit the Mavuzi power plant generating up to a level of 20 MWc, the assurance of supply decreases down to a value of 77%.

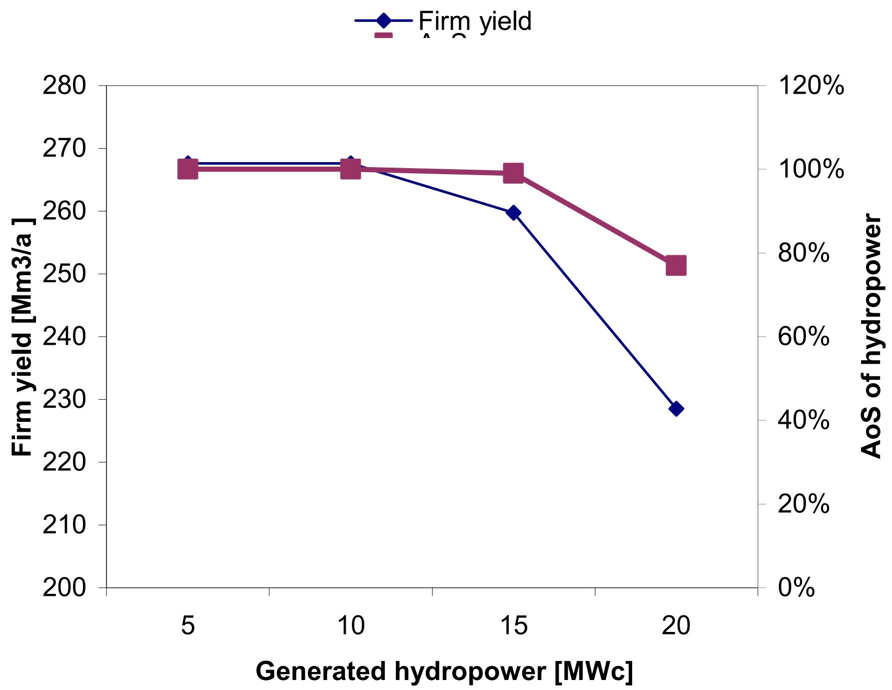

Figure 12 *Firm yield (at the Chicamba dam) and assurance of supplied hydro power (at the Mavuzi dam) with increasing levels of hydropower generation at the Mavuzi dam.*

5.2.3 Impact of EWR on AoS of hydropower

Scenario 4: The AoS at Chicamba with increasing the PES
Scenario 4 represents a further development of Scenario 2, as it simulates the impact of the PES on firm yield and AoS for a certain level of hydropower generation. In case it can be determined that there is a critical level for power generation at 3 MWc for Chicamba (according to the 95% assurance level figure 11), it would be of value to study the impact of increasing values of PES, for that certain hydropower demand. The following result is based on one EWR release from Chicamba with increasing PES, including the power generation maintained at 3 MWc (Table. 6).

Table 6 *Main input parameters for Scenario 4*

Chicamba PES	Mavuzi PES	Chicamba generating power [MWc]	Mavuzi generating power [MWc]
No EWR	-	3	-
C	-	3	-
B/C	-	3	-
B	-	3	-

As seen in figure 13 the amount of available water decreases as the released EWR represaents a higher class of PES. The reference scenario answers to a firm yield of approximately 310 Mm^3/a, which could be compared with the reference scenario in scenrio 1, without any hydropower included. The lowest value of firm yield is attained at class B, with approximately 270 Mm^3/a. The 95% assurance level of hydropower supply is maintained up to PES class C, after which it drops below acceptance level (Figure 13).

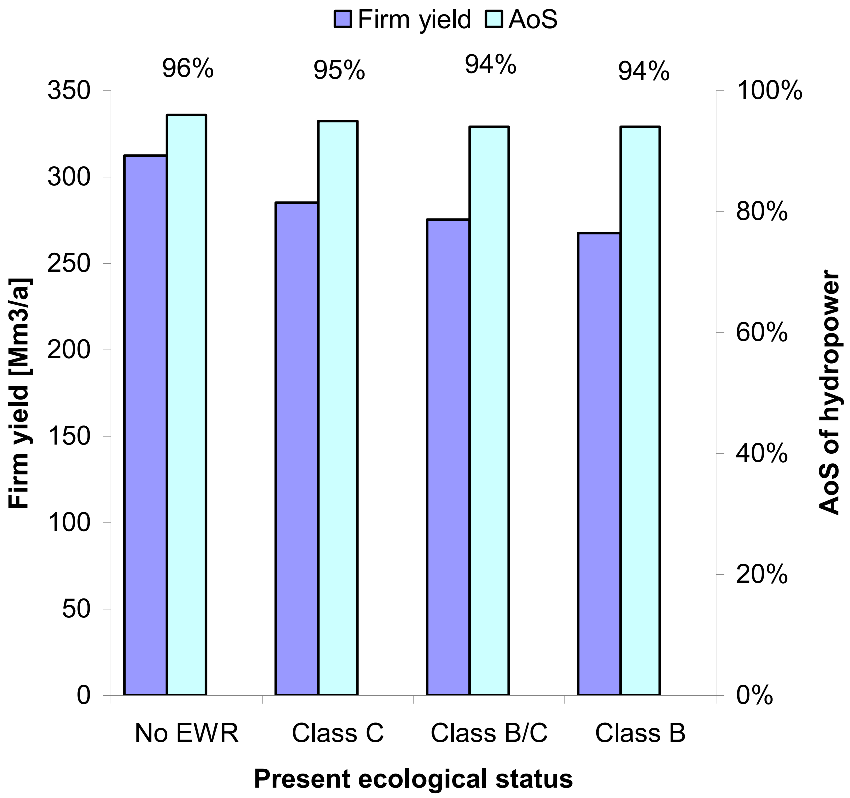

Figure 13 *Firm yield and assurance of supplied hydropower with increasing PES, at the Chicamba dam*

5.2.4 Impact of EWR on firm power

Scenario 5 and 6 show the impact of an EWR release at the Mavuzi dam, with increasing PES. The impact is presented in terms of firm power. The simulations include the Mavuzi power plant, and exclude the upstream Chicamba power plant. There are two environmental flows released with increasing classes of PES (see table 6 and 7), one at Chicamba and one at Mavuzi. The 95 % assurance of hydropower supply is maintained through the simulations.

Scenario 5: Firm power at Mavuzi dam, increasing the PES for Mavuzi
Notable in table 7, this scenario shows firm power with increasing PES of the Mavuzi catchment. The environmental flow released at Chicamba is based on the recommended class B/C.

Table 7 *Main input parameters for Scenario 5*

Chicamba PES	Mavuzi PES	AoS [%]	Chicamba generating power [MWc]
No EWR	No EWR	95	-
B/C	B/C	95	-
B/C	B	95	-
B/C	A/B	95	-

As shown in figure 14 the amount of available power is kept relatively constant as the level of PES increases. The firm power is kept between 38-39 MWc, as for the reference scenario without any environmental flow release. A small reduction in firm yield of approximately1 MWc can be observed from class B/C to class B.

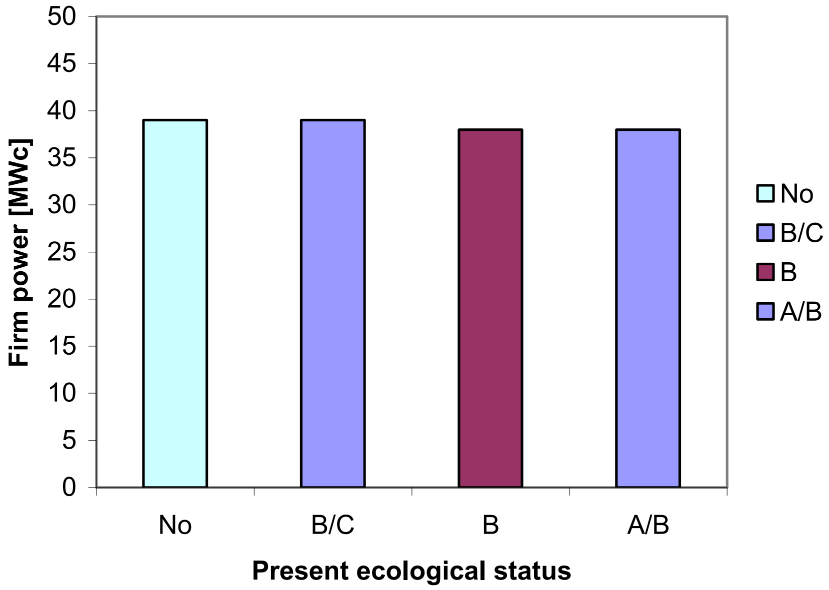

Figure 14 *Firm power at the Mavuzi dam with increasing PES of the Mavuzi catchment*

Scenario 6: Firm power at Mavuzi dam, increasing the PES for Chicamba
The sixth scenario is similar to scenario five except that the PES is increasing for Chicamba and maintained at the recommended class B for Mavuzi (Table. 8). This scenario shows how the set of the PES of Chicamba affects the hydropower capability of the Mavuzi dam.

Table 8 *Main input parameters for Scenario 6*

Chicamba PES	Mavuzi PES	AoS [%]	Chicamba generating power [MWc]
No EWR	No EWR	95	-
C	B	95	-
B/C	B	95	-
B	B	95	-

As seen in figure 15, the Mavuzi firm power is kept relatively constant at approximately 37-38 MWc, when increasing the PES for the Chicamba catchment. There is a small reduction of 2 MWc, going from no environmental water release to an environmental water release of class C. Notable, is a raise in firm power, going from class C to B/C (Figure 15).

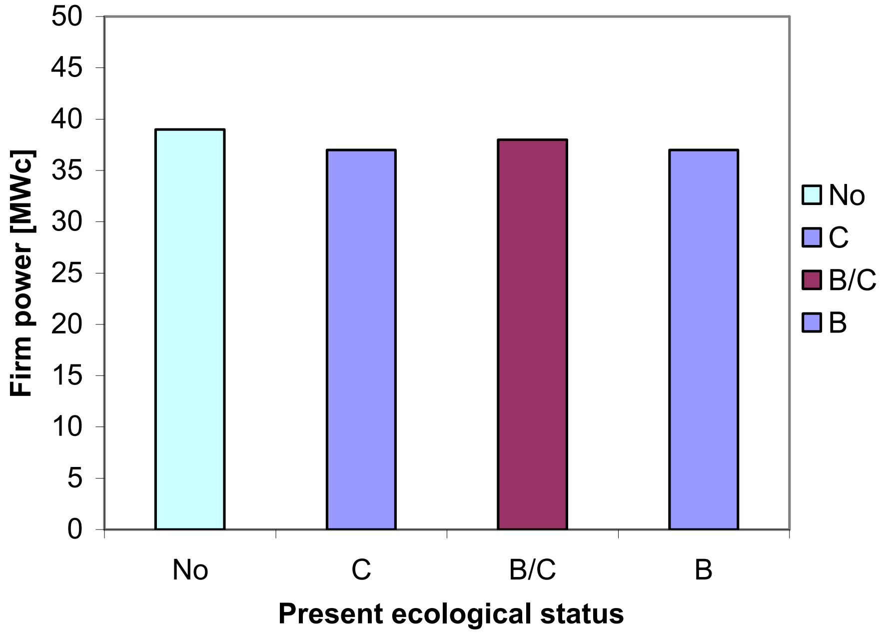

Figure 15 *Firm power at the Mavuzi dam with increasing PES of the Chicamba catchment*

5.2.5 Level of firm power due to location of EWR

Scenario number seven shows a comparison of firm power for the Mavuzi dam and two alternative locations of the environmental flow release. The first location is represented by the spill channel of the Mavuzi dam, and the second location (which is the previous simulated one for Mavuzi) is a bit downstream the power channel, as illustrated in figure 16. The Chicamba power plant is excluded and the assurance of supply of hydropower is maintained at 95 % through simulations. The settings of the PES for the areas can bee seen in table 9.

Table 9 *Main input parameters for Scenario 7*

Chicamba PES	Mavuzi PES	Chicamba generating power [MWc]
No EWR	No EWR	-
B/C	B/C	-
B/C	B	-
B/C	A/B	-

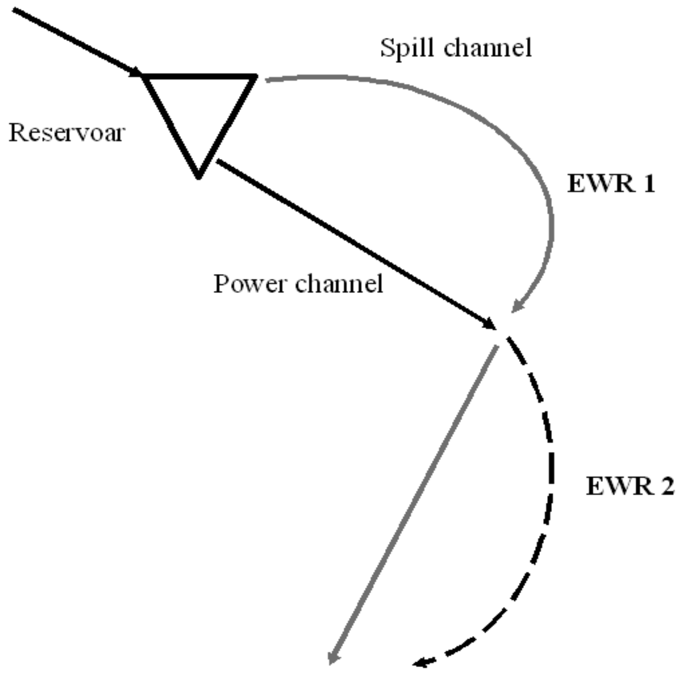

Figure 16 *Alternative locations of an EWR release at the Mavuzi dam. Location number one (grey line) represents the spill channel of the power plant. Location number two, released through the power channel, is located downstream of the power plant.*

Sceanrio 7: Firm power with alternative locations of the EWR release at the Mavuzi dam

As seen in figure 17, firm power is kept constant throughout simulations, regardless the location of the EWR. The first alternative of environmental flow, released through the hydropower spill channel, answers with a relatively constant level of firm power at 23-25 MWc. The second alternative results in a firm power of approximately 38 MWc as the PES increases.

Significant is the difference in firm power between the two alternatives. The first simulated location, released through the hydropower spill channel, is constantly resulting in a lower level of firm power compared to the second simulated location (Figure 17).

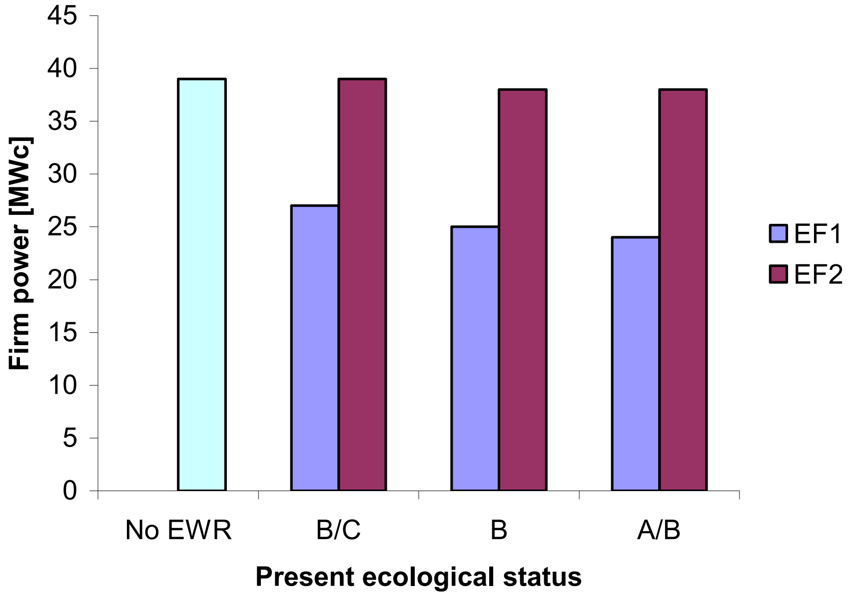

Figure 17 *Firm power with increasing PES, at the Mavuzi dam*

5.2.6 Impact of EWR on available irrigation area

Scenario 8: Maximum irrigation area with increasing PES at the Buzi irrigation system
The eighth scenario assesses the impact of EWR on the maximum available irrigation area for the Buzi Company, with increasing PES. The scenario is based on two upstream EWR releases; one at Chicamba and one at Mavuzi, both at recommended statuses B/C and B. To study the most natural scenario, the Chicamba and Mavuzi plants are operating at close to maximum capacity of 4, 5 and 30 MWc respectively (Table. 10). The purpose of the simulations is to maximize the irrigation area, without exceeding the assurance of supply of 90 %.

Table 10 *Main input parameters for Scenario 8*

Chicamba PES	Mavuzi PES	AoS [%]	Chicamba generating power [MWc]	Mavuzi generating power [MWc]
B/C	B	90	4,5	30
B/C	B	90	4,5	30
B/C	B	90	4,5	30

As seen in figure 18, the available irrigation area decreases significantly with the PES going from class B/C to class A/B. As the PES of the Buzi catchment increases, more water is required to release the environmental flow, and the amount of water available for irrigation decreases. Greatest impact of an EWR is notable going from a class A/B to a class B, with a decreasing effect of 10000 ha in the irrigation area. According to figure 18, the maximum irrigation area that can be developed and supplied at 90 % assurance of supply, corresponding to an environmental flow release based on the recommended class B, is of approximately 35000 ha.

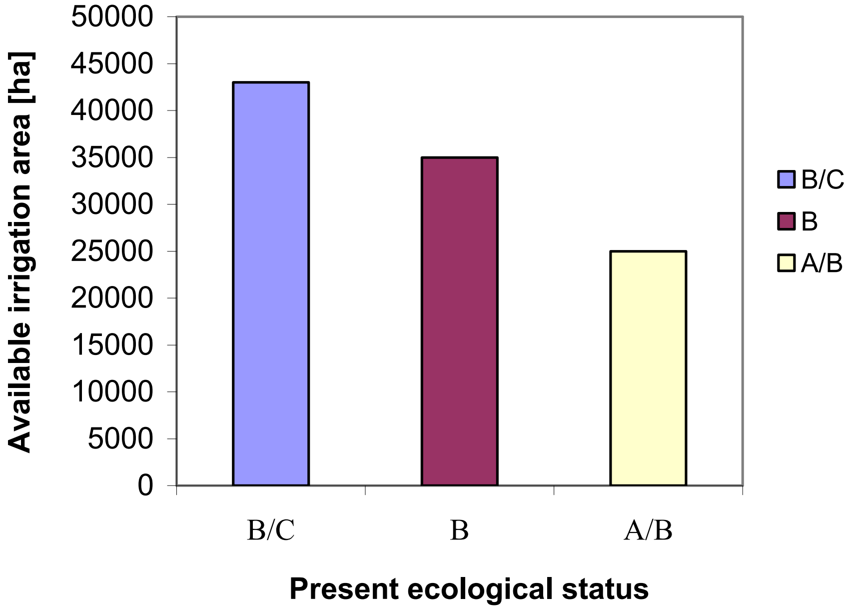

Figure 18 *Available irrigation area with increasing PES at Buzi Company irrigation system*

6 ANALYSIS OF WATER FLOW SCENARIOS

The following section is an analysis of the simulated scenarios and refers to the figures presented in the result section.

Scenario 1
The first simulated scenario argues that EWR releases do have significant impact on the amount of available water with a decrease in firm yield of approximately 200 Mm^3/a between the extremes, going from the "reference scenario" (no EWR) to the PES of class B (Figure10, section 5.2.1). The most likely EWR implementation at the Chicamba dam would correspond to the recommended class B/C, which would result in a 30 % reduction of the available amount of water, according to the result (figure 10).

This result also shows that the difference between implementing and not implementing EWRs has a greater impact on yield than the different classes of the present ecological status (Figure 10).

In terms of the mean annual runoff the yield model calculates approximately 45% of the MAR as firm yield, without any EWR release at the Chicamba dam. Implementing an EWR of the recommended class B/C, firm yield decreases with 25 % of the MAR, going from 45 to 30% of the MAR.

Scenario 2
The second simulated scenario illustrates a significant trade- off between the level of power generation at Chicamba and the amount of available water for consumptive use in the dam (Figure 11, section 5.2.2).

Without competing demands of water at the Chicamba dam, it would be economically viable to maximize the power production for the benefits of the area. However, this is assumed to be the argument of the power producer, such as EDM. On the other hand, with regard to the 95% assurance of hydropower supply the maximum hydropower generation should be reduced with nearly 40%, from a generating level at 4,8 MWc down to approximately 3 MWc. Producing electricity up to levels above 3 MWc results in unacceptable levels (>95%) of supplied electricity, according to the result (figure 11).

The conclusion would be that the power production is limited by the 95% assurance of hydropower supply, rather than the risk of failure of the dam (over abstraction of water) due to hydropower production. According to the results, the Chicamba power plant should not exceed generating levels of 3 MWc in order supply acceptable levels of electricity, within the limits of available water.

Scenario 3
As for the previous scenario, this scenario supports a significant trade-off between the level of generated power and the amount of available water in the Chicamba dam (Figure 12, 5.2.3). An increase in power demand at Mavuzi would strongly reduce the amount of available water at the Chicamba dam. As Chicamba essentially supplies Mavuzi with water for power production, the water consumers at Chicamba are affected, not only by the power production at Chicamba, but also by the power production at Mavuzi.

Furthermore, the results argue for a maximum generating level of approximately 15 MWc at Mavuzi, with regard to the 95 % assurance level. To generate power at levels somewhere just above 15 MWc would result in unacceptable levels of supply to the power consumers of Mavuzi (Figure 12). In order to find the exact critical level of hydropower generation, further simulations between 15 and 20 MWc must be done.

It appears as if the limiting factor of the power production at the Mavuzi dam is the assurance of supply (fig 12).

Scenario 4
With the intent to keep a sufficient AoS (> 95%), an EWR with recommended class B/C appears to have a small negative impact on the power production. According to figure 13 (section 5.2.3), an EWR of class B/C would effect the power production, as the supply of hydropower would drop below the accepted level of AoS. The conclusion would be to briefly reduce the level of power generation if water, allocated the river, is to be released from the dam in the future.

Scenario 5 and 6
The total installed capacity of the Mavuzi dam is originally estimated to 50 MWc (EDM, 2010) but as the AoS is considered at 95%, the capacity is reduced with approximately 20%, without any environmental water releases (Figure 14 and 15, section 5.2.4).

However, comparing scenario five and six shows similar results and the conclusion that introducing EWR would have significant impact on the Mavuzi hydropower capability cannot be supported. Nor is it possible to establish which of the two scenarios that would have greatest impact on the hydropower capability at Mavuzi.

Scenario 7
The second location of the EWR appears to be more profitable for the power consumers in the area as it generates considerable higher amounts of power, according to the result (Figure 17, section 5.2.5). Releasing the environmental flow through the spill channel would however be an environmental benefit for the part of the river that reaches along the spill channel, in particular if the area is considered to be an especially productive habitat.

This is often an issue with hydropower as this configuration on a switchback in the river is favourable due to the gain in head. The length and the ecological status of the river that does not receive the flows (represented by location 1) affect whether power plants can be built and operated in such locations

This scenario also illustrates how downstream EWR decisions impact upstream water consumers, as the Chicamba dam essentially supplies the Mavusi dam with water for hydropower production.

Scenario 8
The last scenario indicates that there is a decrease in maximum area that can be irrigated with water from the Buzi River, when releasing environmental flows at the Buzi irrigation field. The reduction in irrigation area is explained with less water being available for consumptive use as more water becomes required to the river (Figure 10, 5.2.1).

Moreover, compared to water consumption for hydropower, irrigation represents water abstraction for consumptive use, as the water does not return directly to the river. This fact explains the relatively high impact from EWR releases on the irrigation area.

Unfortunately there is no reference scenario included in the simulations why no indication of the present maximum irrigation area is available. A reference scenario would probably have shown a difference in firm yield of a greater extent than illustrated between the classes of PES in figure 18 (section 5.2.6), according to the analysis of scenario 1.

7 DISCUSSION

The Buzi River basin has few large-scale water consumers. With the exception of two hydropower dams and a small number of irrigation systems, the majority of the local population is living out of small-scale rain fed agriculture. Because of this, the people living in the Buzi River basin are relatively independent of direct use of water from the river. Yet both large and small-scale water supply are uncertain during periods, due to the climate, but mainly due to the lack of water regulating infrastructure in the area. The Chicamba dam, situated in the Manica province, is the only large-scale water regulating solution in the Buzi River basin.

With the ability to store water at the Chicamba dam during high flows, more water can be accessible during dry periods. This provides a more continuous supply of water and enables a development of the area that would otherwise not have been possible. The Chicamba dam also contributes to an approved water quality downstream the river. As the area is highly exposed to erosion, the incoming water carries large amounts of sediment. The retention time of the Chicamba reservoir is long enough to allow sedimentation and sand, clay and toxins such as mercury (from upstream gold mining) becomes separated from the water. The sedimentation is a prerequisite for the locals to be able to use the water downstream of Chicamba.

The Chicamba dam is a good example of how water regulating systems such as large-scale dams can contribute to its area with more than only economic and social benefits.

Future development of the Buzi River basin
The result from the water resource analysis, studied in relation to the extent of water use in the area, demonstrates that environmental water requirements would have negligible effects on the water consumers today. However, as the river basin most probably will develop and become more accessible in the future, it is likely to predict both domestic and international investments in the area with businesses that will require water. Such a watershed development would probably increase competing water demands which would make the water consumers more vulnerable to a decrease in the amount of available water. It is therefore plausible that the implementation of environmental water requirements would have a significant negative impact on the water consumers in the future.

When discussing the future development of the river basin one must nevertheless include local circumstances such as political conditions in the area. The power utility of Mozambique, EDM, is very powerful in the region and they control the entire reservoir of the Chicamba dam. With their primary goal of maximising the electricity production, other potential large-scale water consumer would most probably not be able to invest in utilisation of the dam. Considering future water abstraction being limited by EDM, it is not valuable to further discuss potential scenarios with an increased number of stakeholders at Chicamba. Apart from non-consumptive water use such as water use for hydropower, EDM has approved for some small-scale water use by locals in the area. The latter only represents a fraction of the total water consumption at the dam.

Type of water consumption
Analyzing the introduction of EWR and its effects on the production of hydropower, it cannot be concluded that a noticeable negative impact occurs. Hydropower generation represents a non- consumptive water use, as the water is returned to the river, why requirements for both

hydropower and EWR can be met. By releasing water and producing electricity with regard to the environment, EWR releases do not have to affect the production of hydropower.

As opposed to non- consumptive use of water are irrigation systems with their consumptive use of water. Consumptive water use includes water that is evaporated, transpired or incorporated into the growth of vegetables, and this type of water consumption is shown to be more affected by the introduction of environmental water requirements. The analysis of the maximum available area for the irrigation of sugar crops at Buzi Company demonstrates a relatively high impact from implementing EWR. But, with an irrigation area that merely measures 300 ha, it is considered a very small area relative to the area available with EWR. The conclusion is therefore that no negative impact occurs under present circumstances.

Compared to the Chicamba area, the part of the river that is used by the Buzi Company is more likely to be exposed to an increased number of water consuming investors in the future. The EWR impact analysis would have to be re-performed in the future for the Buzi Company, as this area is likely to develop.

Further studies with economic aspects

In order to get a more accurate and complete picture, economic aspects of the introduction of environmental water requirements would also have to be considered. Most preferably the outcome of hydropower generation could be more cost efficient with EWR, especially with releases at the right locations. It is however crucial to prove that the introduction of EWR does not have to be associated with smaller margins for the industries in the region, in order to provide a long term solution. This is often a misassumption in the water using sector because of the lack of information. Results with economic analysis, where both industrial economic long term requirements and environmental requirements are met, could be used as a strong argument when promoting EWR in other parts of the world, where ecosystems are threatened because of water shortage. A complete economic analysis based on the results in this report would also provide valuable directives for the regional water administrations, when developing priority and water allocation systems for the river basin.

This work has shown how relatively simple methods can be used to evaluate the water resource potential of a catchment area for present use, but also with future watershed development. Water resource analysis should be considered a mandatory in water resource management with the purpose to preserve the world's freshwater ecosystems, despite increasing demands on river basins such as Buzi.

CONCLUSIONS

- The amount of available water for consumptive use would be *reduced by approximately 30 %*, when introducing environmental water requirements, to maintain the present ecological status of the area.

- The actual implementation of environmental water requirements has greater impact on the amount of available water for consumptive use, than the class of the present ecological status of the area.

- There is a pronounced relationship between the level off generated hydropower and the amount of water available for consumptive use.

- The limiting factor for power production has proved to be the assurance of hydropower supply, rather than the risk of failure of the system (over abstraction of water).

- The results cannot support the conclusion that introducing environmental water requirements would reduce non-consumptive use of water (represented by hydropower generation).

- Consumptive water use (represented by irrigation) has shown to be more affected by the introduction of environmental water requirements, relative to non-consumptive use of water. Yet the results can not support the conclusion that the irrigation system in question would be negatively affected by the introduction of EWR, since the irrigated area merely measures 300 hectares at present.

- Introducing environmental water requirements downstream the river would affect also the consumers upstream, as the river basin is proved to be an interlinked system.

- The location of the environmental water release, relative to the hydropower plant, can have significant impact on the hydropower capability of the system. Potential ecological impacts of flow modifications would need to be assessed, relative the gain in hydropower generation.

- Introducing environmental water requirements in the Buzi River basin is assumed not to have significant negative impact on the water consumers at present. Taking future development of the river basin into account, it would be necessary to make a new analysis of the area to establish the impact.

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8 APPENDIX A

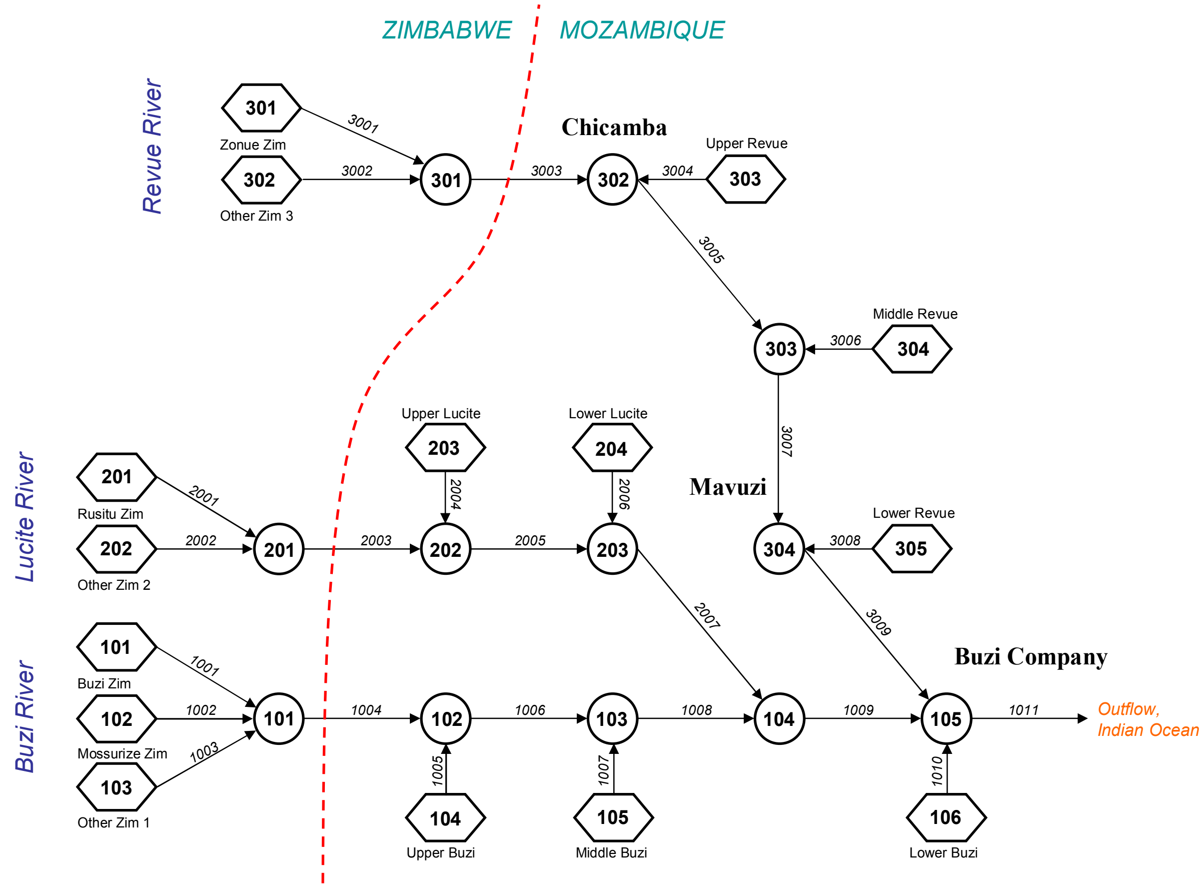

Figure 19 *The Pitman flow schematic network of the Buzi River basin (Sweco, 2010)*

MAR for Buzi River sub-catchments

The mean annual runoff for a specific sub-catchment is essentially calculated as the sum of the MAR of all upstream sub-catchments (see flow schematic network for details, Figure19).

Chicamba dam

The cumulative MAR of the Chicamba catchment includes the mean annual runoff from the sub-catchments represented by following channels:
3003+3004 => MAR= 1218 Mm^3/a

Mavuzi dam

The cumulative MAR of the Mavuzi catchment includes the mean annual runoff from the sub-catchments represented by following channels:
3007+0, 05 * 3008 => MAR= 2000 Mm^3/a

Buzi Company sugar plantation

The cumulative MAR of the Buzi irrigation catchment includes the mean annual runoff from the sub-catchments represented by following channels:
1009+3009+0, 25*1010 => MAR= 7170 Mm^3/a

9 APPENDIX B

Approximations of RAN data
All the sub-catchments with inadequate RAN data have been approximated to RAN data for the Chicamba and the Beira catchment (according to table 11).

In purpose to show which area was being approximated with which RAN-file, the below table is attached into the appendix.

Table 11 *The 15 sub-catchments within the Buzi River basin and their approximations of RAN data (The "Pitman code" refers to the schematic flow diagram in Appendix A, Figure19).*

Main River	Sub-catchment	Pitman code	RAN-file
BUZI	Buzi Zim	101	Chica.ran
	Mossurize Zim	102	Chica.ran
	Other Zim 1	103	Chica.ran
	Upper Buzi	104	Beira.ran
	Middle Buzi	105	Beira.ran
	Lower Buzi	106	Beira.ran
LUCITE	Rusitu Zim	201	Chica.ran
	Other Zim 2	202	Chica.ran
	Upper Lucite	203	Chica.ran
	Lower Lucite	204	Beira.ran
REVUE	Zonue Zim	301	Chica.ran
	Other Zim 3	302	Chica.ran
	Upper Revue	303	Chica.ran
	Middle Revue	304	Chica.ran
	Lower Revue	305	Beira.ran

10 APPENDIX C

Table 12 *Technical characteristics for the Chicamba dam*

Reservoir		**Power plant**	
Dam cap. At FSL [Mm3]	2000	Turbine cap. 1 [MW]	24
Surface area at FSL [km2]	120	Turbine cap. 2 [MW]	24
FSL [m.a.s.l.]	625	Total unit cap. [MW]	48
DSL [m.a.s.l.]	590		
TWE [m.a.s.l.]	565		
Head [m]	52		
Min. head [m]	25		
Max. head [m]	60		
Head loss	2		

Table 13 *Technical characteristics for the Mavuzi dam*

Reservoir		**Power plant**	
Dam cap. [Mm^3]	1,8	Turbine cap. 1 [MW]	5,5
Surface area [km2]	26	Turbine cap. 2 [MW]	5,5
FSL [m.a.s.l.]	345	Turbine cap. 3 [MW]	13
DSL [m.a.s.l.]	343	Turbine cap. 4 [MW]	13
TWE [m.a.s.l.]	165	Turbine cap. 5 [MW]	13
Head [m]	160	Total unit cap. [MW]	50
Min. head [m]	156		
Max. head [m]	150		
Head loss	5		

Table 14 *Technical characteristics for the Buzi Company irrigation system*

Irrigation system	
Crop	Sugar
Irrigation area [ha]	300
Irrigation efficiency factor	0,7
Return flow factor	0,08
Monthly effective rainfall	0,75

11 APPENDIX D

List of figures and tables

Figures	**Page**

Tables	**Page**